Dynamics of fluvial fine sediment transfer in the River Esk, North Yorkshire, UK

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Declaration

This thesis is the result of my own work and has not been submitted for consideration in any other examination. Material from the work of other authors, which is referred to in the thesis, is acknowledged in the text.

Statement of copyright

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Abstract

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A full understanding of the complexities of fluvial suspended sediment dynamics requires a holistic approach. The study presented here addresses fine sediment transfer in the River Esk catchment, which is suffering from the adverse effects of increased fine sediment flux, in particular the silting up of salmon and sea trout spawning habitats and pearl mussel beds. Time-integrated mass flux sampling was used to monitor relative suspended sediment loads at 17 locations in the catchment. This was combined with water sampling, turbidity and stage monitoring at two locations which provided measurements of suspended sediment and its relation to flow at a high temporal resolution. A GIS database for the main Esk and major tributaries was constructed, containing channel and riparian attributes relevant to fine sediment transfer. These were obtained from detailed attribute mapping. The monitoring results were related to these mapped characteristics

Relative specific suspended sediment yields were found not to be solely related to catchment area, but were more dependent on the varying substrates and the land use intensity in the sub-catchments. Suspended sediment transport was supply-limited and subject to exhaustion effects. The most common type of hysteresis was clockwise, which occurred in large events where sediment supplies were abundant, while anticlockwise hysteresis was restricted to events where peak suspended sediment concentration was low. It was inferred that the dominant source of fine sediment to the Esk is from in-channel sources, primarily bank erosion and storage of sediment on the channel bed. Livestock poaching increased bank erosion in one reach of the main Esk and in several tributaries. Sediment transport in the Esk is sensitive to high flows, when sediment from in-channel sources is flushed through the system. Sudden increases in suspended sediment concentrations between and within storms showed recharge of sediment supplies to be episodic, probably related to bank failure or removal of debris jams. Management of fine sediment in the Esk should be targeted at reducing in-channel sediment supply to the flow in the upper main channel and in the tributaries of Glaisdale, Great Fryup and Butter Becks.

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1. Introduction

1.1. Background

Concern for effective river and catchment management is currently increasing as awareness grows of issues such as water quality, soil erosion and flooding. Population and industrial growth, increasing recreational use and climate changes combine to put greater pressure on water resources. The consequences of this are that sustainable management of water resources and their catchments is essential (Walling, 1995; Burt, 2001). In recent years a move towards an integrated approach to river management at the catchment scale has been proposed by various authorities (Burt, 1999). The EU Water Framework Directive, introduced in 2000, has embraced the view that management of the river basin as a unit is the most effective method and has thus stipulated the development of river basin management plans. The advantage of this method of integrated catchment management is that it comprises a holistic approach, taking into account the interactions of catchment processes, different land uses, the needs of users of the catchment and the way in which these affect, and are affected by, hydrological processes (Burt, 2001).

An increase in fine sediment flux is a recent feature of many upland river channels. High levels of fine sediment in rivers can have negative effects for several reasons and is a problem facing many catchment managers. Fine sediment forms a vehicle for the transport into rivers of contaminants from industrial or agricultural land, such as pesticides and fertilisers (Stott and Burt, 1997), which damage in-stream habitats through eutrophication or poisoning of biota (Boardman and Favis-Mortlock, 1993). A high fine sediment load can increase levels of reservoir siltation, reducing reservoir capacity, while high turbidity reduces light penetration into the water column, limiting photosynthesis levels. Siltation of gravel-bed streams by high sediment loads is detrimental to in-stream habitats (Wood and Armitage, 1997; Armstrong *et al.*, 2003) damaging stream ecosystems and can have a negative economic impact on fishing industries.

The reasons for increased fine sediment loads in rivers may include changes to the climatic regime, land disturbance and changes in land use or management practices (Foster and Lees, 1999; Syvitski, 2003; Owens *et al.,* 2005). A greater understanding of how fine sediment dynamics respond to different conditions will help to predict future changes in flux and inform management plans to mitigate any negative effects these changes might have on river systems (Syvitski, 2003). The understanding of fine sediment dynamics can also inform understanding of the related issues of soil erosion, bank erosion and runoff patterns within the catchment and thus makes an important contribution to the overall understanding of catchment processes.

A good example of a river affected by high levels of fine sediment is the River Esk in North Yorkshire, UK (Bracken and Warburton, 2005). It has been suggested that recent declines in pearl mussel and salmonid numbers in the Esk can be attributed to the declining quality of in-stream habitat due to fine sediment accumulation. A high proportion of fine sediment in river-bed gravels clogs up interstitial pores and prevents the circulation of oxygen to buried salmon and trout eggs, reducing the success of hatching (Armstrong *et al.*, 2003; Hendry and Cragg-Hine, 2003). It can also cause suffocation of juvenile pearl mussels (Skinner *et al.,* 2003). Salmon and pearl mussels are both priority species in the UK Biodiversity Action Plan and are protected by UK and EU legislation, including the Wildlife and Countryside Act (1981), Freshwater Fish Directive and Habitats Directive. The Esk is of regional significance as a salmon and sea trout spawning ground and the fisheries are an important part of the local economy. It is essential that the sediment input to the stream is managed to prevent further decline in these species and their habitats. In order to do this, an understanding of fine sediment transfers at the catchment scale is required, so that effective measures can be put in place.

1.2. Research Context

A river catchment comprises different morphological and process units such as hillslopes, floodplain and river. However, the processes occurring within each of these units has an influence on processes occurring elsewhere in the catchment, linking all parts of the catchment to create a complex and integrated system (Owens *et al.,* 2005). The transfer of fine sediment is a good example of a process which links all parts of the catchment and is therefore affected by many factors at a range of different scales. This makes fine sediment transfer a difficult process to understand and quantify. Many studies have been undertaken with the objective of discovering the sources of fine sediment in catchments (e.g. Walling *et al.,* 1999; Minella *et al.*, 2004) and the mechanisms of fine sediment transfer (e.g. Olive and Rieger, 1985; Brasington and Richards, 2000). Various techniques have been employed, including the use of sediment properties or radionuclides to trace sediments to a source (e.g. Collins *et al.*, 1998; Gruszowski *et al.,* 2003); analysing storm hysteresis plots to show temporal variability in sediment input (e.g. Wood, 1977; Klein, 1984); or trying to relate sediment yield data to estimates of soil erosion and form a catchment sediment budget (e.g. Foster *et al.*, 1996). However there is still much uncertainty over the importance of different transfer mechanisms, especially relating to the role of sediment storage within the catchment, which modifies the relationship between the amount of sediment erosion and transport and the suspended sediment levels in the stream (Walling, 1983; Walling and Webb, 1987).

Complexity of the processes and variability in influencing factors, such as soils, land uses and climate, cause sediment flux dynamics to vary greatly between catchments and make meaningful general models difficult to obtain. However, most studies show that magnitude-frequency effects are important in suspended sediment transfer, where low frequency flood events usually account for a high proportion of sediment transport (e.g. Olive and Rieger, 1985; Slattery and Burt, 1996). Relationships between storm characteristics and suspended sediment transport are often characterised by thresholds of sediment transport and deposition and non-linear responses (e.g. Hicks *et al.,* 2000; Burt, 2001; Syvitski, 2003; Nistor and Church, 2004). Studies also show that hysteresis effects characterise a large number of sediment transport regimes and that these are most commonly due to sediment exhaustion effects (e.g. Wood, 1977; Carling, 1983; Batalla and Sala, 1994). Seasonal variations in sediment transfer, which arise from the influence of the climatic regime, seasonal land use changes and system 'memory', are an important characteristic of many catchments (e.g. Brasington and Richards 2000; Nistor and Church 2004).

1.3. Aims and Objectives

This project seeks to use an innovative combination of sediment monitoring at different temporal and spatial resolutions and observation of catchment characteristics, in order to gain a more holistic understanding of the fine sediment transport processes operating in the River Esk than has been achieved for rivers in other, similar studies. The aim of this research, then, is to understand the spatial and temporal patterns in suspended sediment flux during storms, especially the influence of catchment and storm characteristics, and use this to gain a better understanding of how fine sediment production processes and transfer mechanisms operate in the upper Esk catchment.

In order to meet this aim, the following objectives will be addressed:

1. Quantify the spatial variation in suspended sediment yields within the Esk catchment;
2. Determine whether suspended sediment concentration (SSC) during storms is related to the supply of sediment available for transport;
3. Infer dominant processes of fine sediment input during floods by investigating between- and within-storm suspended sediment dynamics;
4. Assess the effect of spatial variability in channel and catchment characteristics on relationships between flow and suspended sediment transport;

1.4 Study Site

1.4.1. River and catchment characteristics

The River Esk catchment, which has an area of 362 km^2, is situated in the North York Moors National Park, Northern England (Figure 1.1). The River Esk flows 42 km from west to east, entering the North Sea at Whitby. The highest point of the moorland drained by the Esk is 432 m above sea level (Figure 1.2). The Esk upstream of Grosmont will be the focus of this study because the upper part of the catchment is where salmon spawning sites are most abundant and are most vulnerable to pollution by fine sediment. The focus on the upper part of the catchment also enabled the project to be manageable over a one-year timescale.

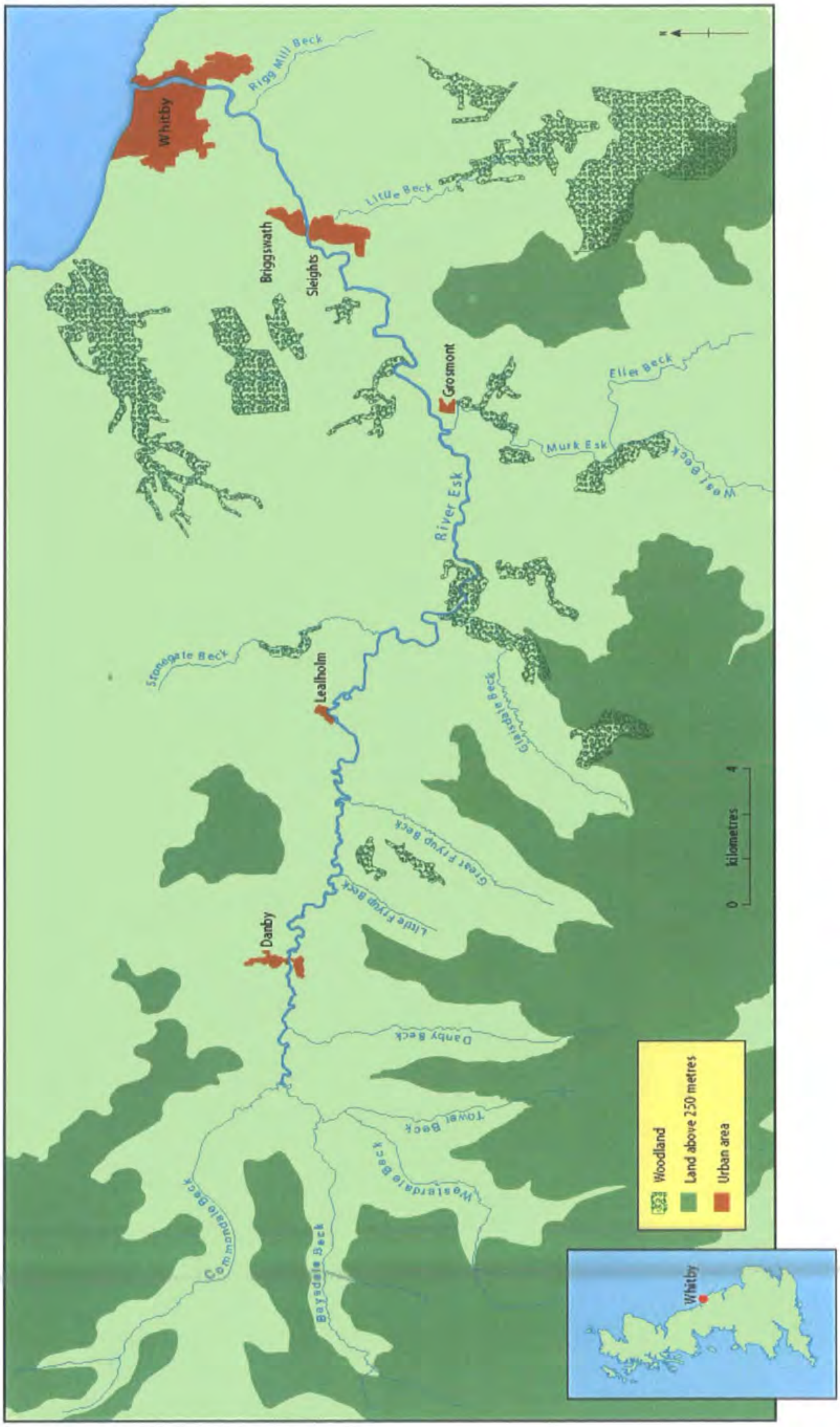


Figure 1.1. The River Esk catchment and its location in Britain.

The majority of the upper Esk has a gravel bed, but there is a large variation in mean grain size; boulders are present in places and some reaches have a sandy bed. When not in flood, flow in the river is generally shallow, often consisting of pool and riffle sequences. River and catchment morphology show significant variation along the length of the river. Upstream of Lealholm and downstream of Glaisdale the channel has a gentle gradient and meanders across a 200- 300 m wide floodplain. In reaches between Lealholm and Glaisdale, however, bedrock control of channel morphology has resulted in reaches consisting of rapids, waterfalls, bedrock gorges and a narrower or non-existent floodplain (Figure 1.2).

Two main sites, Danby and Grosmont (Figure 1.1), were used for monitoring flow, rainfall and SSC, in order that upstream and downstream patterns of sediment flux can be compared. Danby is approximately 10 km downstream of the headwaters of the Esk and Grosmont is approximately 14 km further downstream; they have catchment areas of 107 km^2 and 297 km^2 respectively. At Danby the river is incised with steep banks, prone to slumping. Bankfull width and mean depth are approximately 9 m and 1.8 m respectively (Figure 1.3 A). At Grosmont the channel is less incised. Bankfull width is approximately 25 m and the mean bankfull depth is approximately 1.5 m (Figure 1.3 B). Bankfull discharge at Danby was calculated from flow gauging to be 15 $m^2 s^{-1}$; using the bankfull cross sectional area bankfull discharge was estimated to be 34 $m^2 s^{-1}$ at Grosmont.

Above Danby the headwater tributaries, including Danby Beck, Tower Beck, Westerdale Esk, Baysdale Beck and Commondale Beck, flow in from the moorland of the south and west to form the main Esk (Figure 1.1). Between Danby and Grosmont flow inputs to the river include the tributaries of Great and Little Fryup Becks, Stonegate Beck, Glaisdale Beck, the Murk Esk and numerous smaller tributaries. All of the major tributaries drain the moorland plateaux on the south and west sides of the catchment and flow north or east, except for Stonegate Beck, which flows in from the north. The catchments of these tributaries are generally steep sided with open grass and heather moorland on the valley sides, heads and interfluves. In the valley bottoms pasture is the main land use, with a small amount of arable farming and some small settlements. Some of the valley sides and heads, such as the east of Glaisdale are wooded, partly with plantations. Woodland accounts for approximately 10 percent of the total catchment area of the Esk (EA, 2005). The Murk Esk is a major tributary, draining a catchment area of approximately 90 km². It flows northwards to join the main Esk at Grosmont and is itself comprised of two tributaries, West Beck and Eller Beck. The catchment of the Murk Esk has varying land use, with a significant amount of woodland and moorland, as well as pasture and settlements including the village of Goathland. Parts of the Murk Esk are deeply incised, flowing through steep-sided gorges, such as at Beck Hole. Table 1.1 summarises the main tributaries of the upper Esk and their catchment areas.

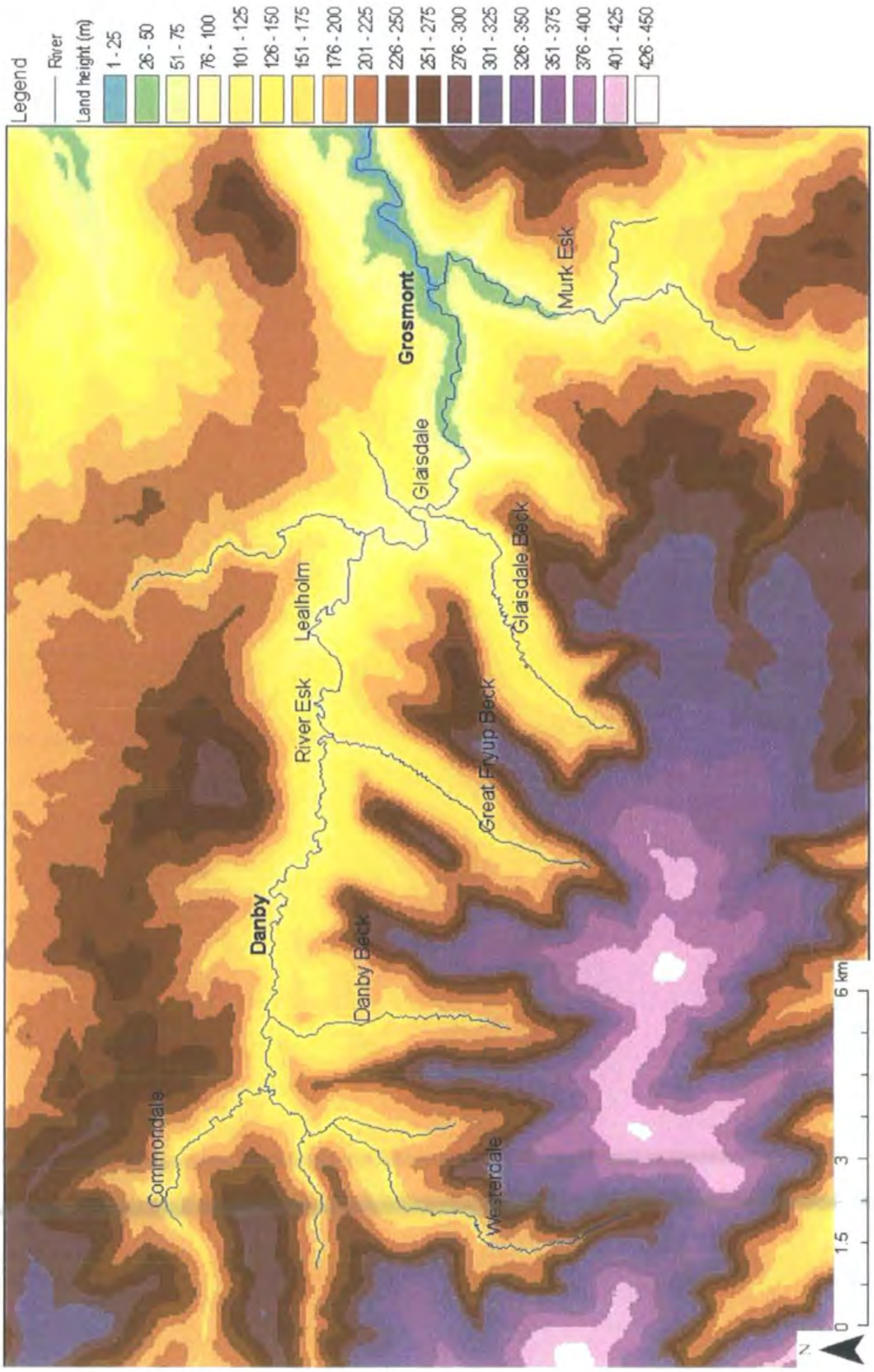


Figure 1.2. Elevation of the upper Esk catchment (data from Edina Digimap).

A

B

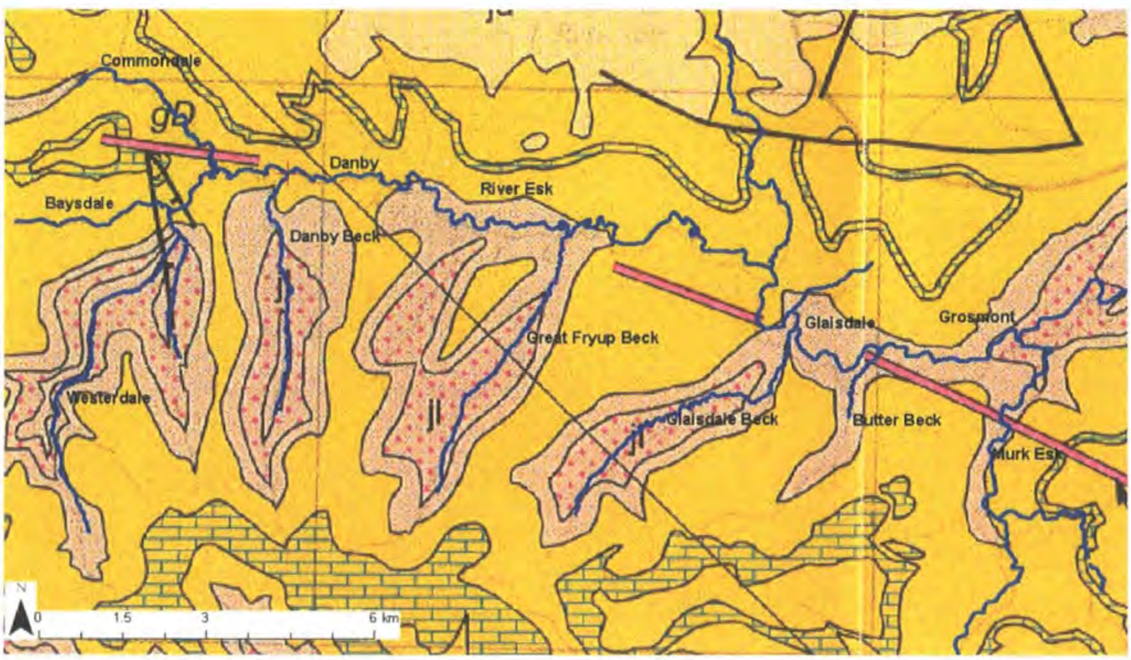
Figure 1.3. The two main monitoring sites: A) high flow at Danby, looking upstream; B) high flow at Grosmont, looking upstream.

Table 1.1. Main tributaries of the Esk, and their catchment areas (from EA, 2005)

Tributary	Catchment area (km^2)
Murk Esk	89.6
Commondale Beck	25.1
Baysdale Beck	20.0
Glaisdale Beck	15.6
Great Fryup Beck	14.4
Stonegate Beck	13.3
Danby Beck	12.4
Butter Beck	9.1
Little Fryup Beck	4.3

1.4.2. Geology

The catchment is underlain by the massive sandstones, shales and limestones of the mid-Jurassic Ravenscar Group, which form the high moorlands (Figure 1.4). Parts of Eskdale, mainly in the south, and parts of the Murk Esk are carved into the easily eroded Lias shales (Staniforth, 1993). The geological characteristics result in negligible groundwater contribution to floods on the Esk (EA, 2005). An ice lobe from the North Sea penetrated Eskdale during the Devensian period, depositing extensive boulder clays, sands and gravels (Figure 1.5). It has been suggested that a glacial lake, with its outflow down Eskdale, existed above Lealholm, depositing lacustrine sediments where the valley is broader (Eyre and Palmer, 1973; Staniforth, 1993). Alluvium deposits are present in the valleys of the Esk and its tributaries, though their extent is limited by the steep valley sides (EA, 2005). The extent of these soft sediments has the potential to affect rates and processes of fine sediment supply to the river.



Cleveland Dike · Middle Jurassic · Middle Jurassic (limestone) · Lower Jurassic · Lower Jurassic (ironstone and sandstone) · River Esk

Figure 1.4. Solid geology of the Esk catchment (British Geological Survey, 1995).

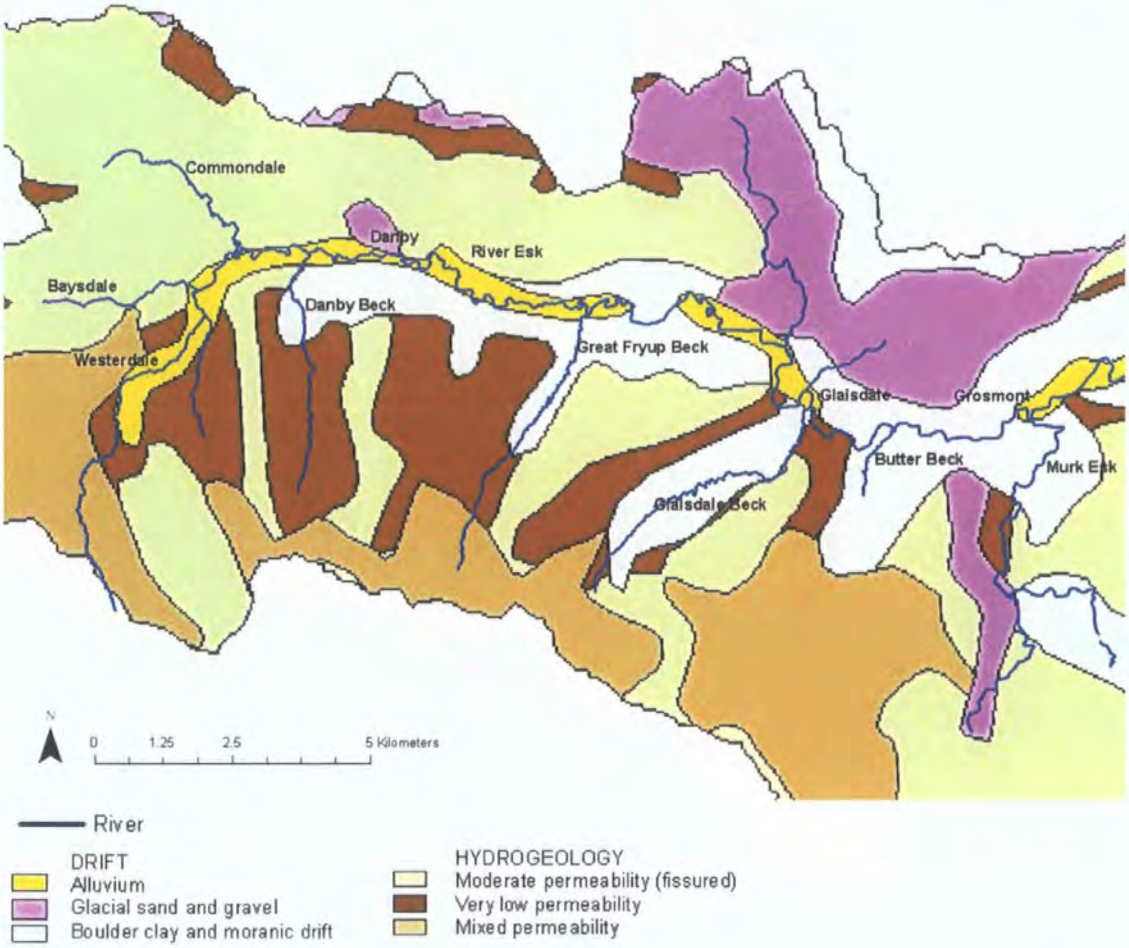


Figure 1.5. Hydrogeology and drift of the Esk catchment (adapted from EA, 2005).

1.4.3. Climate

The climate in the Esk catchment is cold and wet temperate. Mean temperatures are 2°C in January and 16°C in August. Snow lies for an average of 40 days per year on high ground, and 15-20 days on lower ground (Carroll and Bendelow, 1981). Mean annual precipitation is between 700 and 1000 mm and highest rainfall totals are on the high moors to the west and south of the catchment (EA, 2005). Most rain is delivered through frontal storms which can occur at any time of year, although the majority occur during the winter. High-intensity rainfall occurs in the summer, as convective storms. Recent precipitation trends, however, suggest that heavy winter precipitation is becoming more common in the UK, and that summer precipitation totals are decreasing (Osborn and Hulme, 2002). Northern England shares this trend, and climate change forecasts suggest that there is likely to be a change in precipitation distribution towards a greater summer-winter contrast and a higher number of heavy rainfall days (Longfield and Macklin, 1999). This is likely to affect the runoff and sediment transport characteristics of the Esk.

1.4.4. Soils, vegetation and land use

On the highest interfluves peat can be found, with a depth of around two metres. Bogs may also be found in waterlogged pockets. Elsewhere on higher ground stagnohumic gleys, podzols and stagnopodzols dominate. Pelosols are present on the upper slopes of several of the tributary valleys, including Westerdale, Danby Dale, Great and Little Fryupdales and Glaisdale. In the valleys brown earths and stagnogleys can be found (Carroll and Bendelow 1981).

The vegetation in the upper parts of the catchment consists of moorland with heather as the dominant species, although bilberry, bracken and grasses are also present. The extent of blanket bogs and their associated community of mosses and cotton grasses have declined due to artificial draining and burning of the moors (Eyre and Palmer, 1973). Moorland areas are maintained for sheep grazing and grouse shooting, which involves regular burning of parts of the moor in order to promote the growth of new heather shoots to provide food for the birds. Following burning, plants other that heather may become dominant for a short time and erosion may increase, until the cover of heather becomes re-established. Gripping and moorland drainage is also a common practice, and may cause flashier hydrograph characteristics (EA, 2005).

Historically forest has been cleared from upland parts of the catchment, but some has been replaced with coniferous plantations, for example in Glaisdale and Danby High Moor (EA, 2005). Broad-leaved woodland, some of which is ancient can also be found. In the catchment as a whole much of the land is of low agricultural value and is used for dairy farming and sheep pasture, with a smaller area used for arable crops (Table 1.2). The catchment is entirely rural with minor settlements found along the valleys of the main Esk and the Murk Esk. As well as farming, grouse shooting and fishing, an important economic activity in the area is tourism.

Table 1.2. Land use in the Esk catchment. (From EA, 2005)

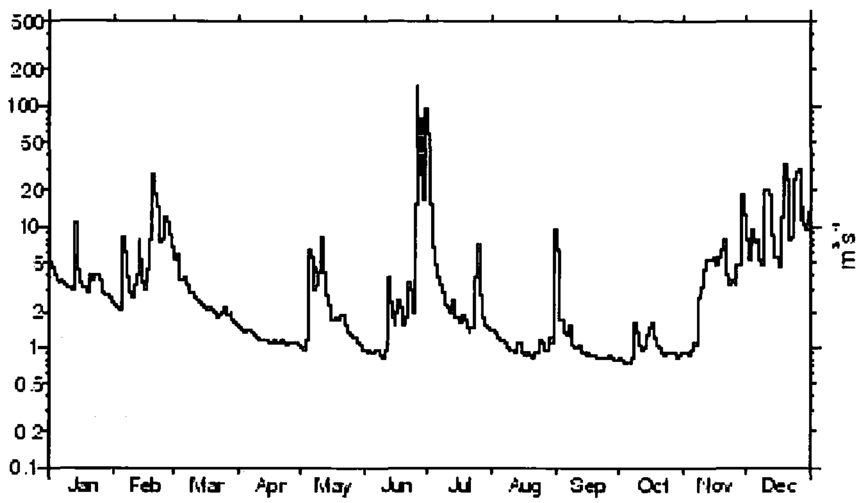
Land use	**% cover**
Mountain, heath, bog	47.7
Grassland	31.8
Woodland	9.8
Arable & horticulture	8.3
Built-up areas	2.4

1.4.5. Flow and suspended sediment characteristics

The river has a flashy regime with sharp flood peaks (Figure 1.6 A), a consequence of the steep-sided catchment and generally narrow floodplain which allows a rapid transfer of runoff to the river and little attenuation of flood peaks. Peaty soils on the high ground produce runoff quickly during rain, adding to the flashiness of flow peaks. The Esk floods regularly and bankfull discharges occur several times per year. Figure 1.6 B shows that mean discharge at Sleights (6 km downstream of Grosmont; Figure 1.1) is higher in the winter, but the summer is characterised by some high flood peaks, relative to the seasonal mean discharge.

Suspended sediment transport in the Esk catchment has been shown to be high during floods and is having detrimental effects on the in-stream habitats (EA, 2005). According to Bracken and Warburton (2005) SSC varies between 5 mg l^{-1} at low flow and over 300 mg l^{-1} at high flows. This range is similar to those cited for other catchments in Northern England (Carling, 1983; Klein, 1984; Armstrong, 2005). Bracken and Warburton (2005) showed that SSC is highly variable, both within and between storms. Bank erosion is thought to be the main source of sediment supply, particularly in the upper part of the catchment (Bracken and Warburton, 2005; EA, 2005). Positive hysteresis of SSC has been shown to occur within storms at both Danby and Grosmont. A sediment exhaustion effect was also apparent over a series of floods. This is thought to be due to exhaustion of sediment supplies during storms (Bracken and Warburton 2005), which may reflect the dominance of bank erosion as a sediment source. This project will expand upon the existing research on the Esk in order to explore sediment transfer dynamics in more depth, particularly the way in which they relate to storm and catchment characteristics and the sediment input mechanisms that can be inferred from this.

A



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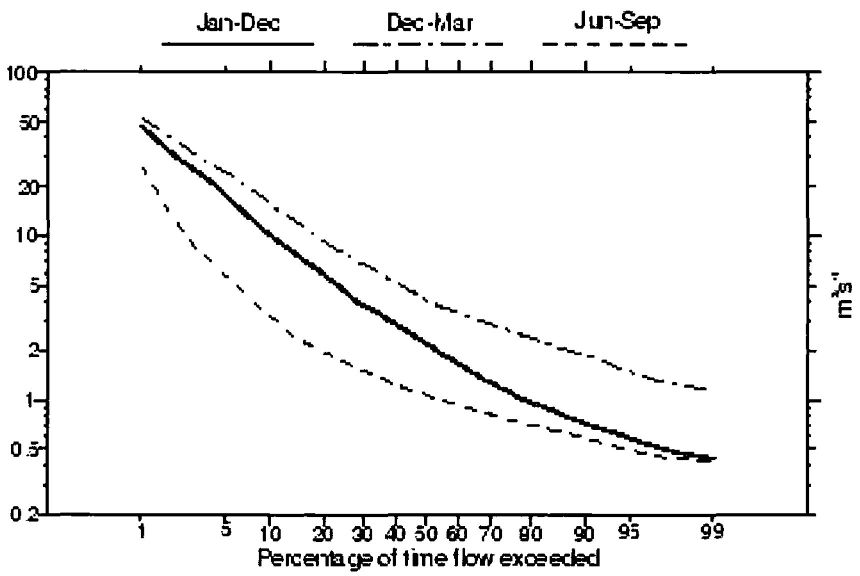

Figure 1.6. A) Maximum and minimum daily flows for the River Esk at Sleights between 1970 and 1997, with flow in 1997 (solid line); B) Flow duration curve for gauged daily flows on the Esk at Sleights between 1970 and 1997 (National River Flow Archive).

1.5. Thesis Outline

This introductory chapter has provided a background to the thesis and a justification for the research. The following chapter expands on this by reviewing literature relevant to the study of fluvial fine sediment transfer dynamics. Chapter 3 reviews methods of suspended sediment monitoring, before describing the methods adopted by this study. In Chapter 4 spatial variability in suspended sediment loads and specific sediment yields in the Esk are examined. These variations are related to catchment area and to spatial variability in mapped channel and catchment characteristics, in order to show the dominant areas of the catchment for sediment transfer. Temporal trends in fine sediment transfer are addressed in Chapter 5, where relationships between SSC and discharge are analysed in relation to storm characteristics. Together with knowledge of channel and catchment form these are used to infer sediment input mechanisms. Chapter 6 brings together the results of the spatial and temporal aspects of the study presented in the previous two chapters in order to understand the overall dynamics of fine sediment in the Esk. This chapter also discusses the implications of the findings for fine sediment management. The conclusions of the study, its limitations and the scope for further work are presented in Chapter 7.

2. Literature Review

2.1. Introduction

The wide relevance of suspended sediment dynamics to geomorphological, engineering, ecological and land-use-related problems has resulted in a large number of studies on this topic. This chapter reviews the literature relevant to the study of the dynamics of fine sediment fluxes in the River Esk. Literature relating to the variations in the magnitude of suspended sediment fluxes is discussed, focussing firstly on spatial variations and the relationship with catchment area, followed by between-storm and within-storm variability in SSC. This is linked to a discussion of the various processes contributing to fine sediment supply in rivers, and how these cause variation in the magnitude of suspended sediment fluxes. Finally, the important concepts from the literature which relate to this study are summarised and discuss gaps that exist are discussed. Literature relevant to the measuring of suspended sediment dynamics is reviewed at the beginning of Chapter 3.

2.2. Patterns of suspended sediment flux

Understanding suspended sediment behaviour in a channel gives insight into the way in which fine sediment is transported and stored in the river system. This may include the response to spatial and temporal variations in catchment characteristics and types of sediment transporting events. Studies of different aspects of fluvial fine sediment behaviour will now be discussed.

2.2.1. Spatial patterns of suspended sediment yield

Spatial variations in sediment sources and transfer processes occur within a catchment and lead to downstream variability in suspended sediment flux. Although total sediment yield generally increases downstream because of the larger contributing area (Bull *et al.,* 1995), specific sediment yield (sediment yield per unit of source area) has often been found to have an inverse relationship with catchment area (Walling, 1983;

Knighton, 1987). However, the relationship is not a straightforward one and is dependent on the catchment characteristics. Larger catchment areas have greater opportunities for storage of sediment (Meade, 1982; Walling, 1983). Floodplains act as a buffer between hillslope sediment sources and the river (Bull *et al.,* 1995) and act as storage areas for sediment deposited by overbank flows, thereby reducing the volume of sediment reaching the catchment outlet (Prestegaard, 1988; Foster *et al.,* 1996). Smaller catchments generally have smaller or non-existent floodplains, so hillslope sources have a greater connectivity with the river (e.g. Harvey, 1994) and overbank flooding is less able to deposit sediment. Small headwater catchments also have steeper hillslopes, which are more likely to produce runoff with a greater capacity to transport sediment to the river and these streams are often more actively incising and therefore producing sediment (Prestegaard, 1988). In a study of rivers in Devon, Webb and Walling (1984) suggest that the small catchment area of the Dart (46 km^2) allows a greater degree of catchment wetness and, therefore, connectivity between sources and the river than for the larger Barle (128 km^2) and Creedy (262 km^2) catchments, for a storm of a given size.

In contrast to these studies, a positive relationship between specific sediment yield and catchment area has been reported in other investigations. In British Colombia sediment yields were found to increase downstream because secondary erosion of Quaternary glacial deposits in larger catchment areas produced more sediment than primary denudation in smaller, undisturbed, upland catchments (Church and Slaymaker, 1989). Similarly, although Bull *et al.,* (1995) found an initial decrease in specific sediment yield with increasing catchment area in the upper River Severn (catchment area 335 km^2), due to decreasing input from catchment sources, this was more than compensated for in lower reaches by an increase in sediment input from bank erosion. This resulted in an overall increase in specific sediment yield with increasing basin area. Prestegaard (1988) found an increase in the relative contribution of bank erosion sources compared to hillslope sources in the downstream direction in a Pennsylvanian basin (catchment area 414 km^2), however specific sediment yield was found to remain constant downstream, indicating that bank erosion was of less importance as a source than in the River Severn.

The relationship between sediment yield and basin area may be affected by changing catchment processes or land use downstream. For example, Bathurst *et al.,* (2005) found that in the Eden basin estimated specific suspended sediment yields showed an initial increase with increasing catchment area, followed by an overall decrease (Figure 2.1). Field observation showed that the intensification of farming and higher stocking densities in the lower reaches of the catchment caused high suspended sediment yields compared to the upland reaches and may have prevented a more pronounced decrease in specific sediment yield with catchment area.

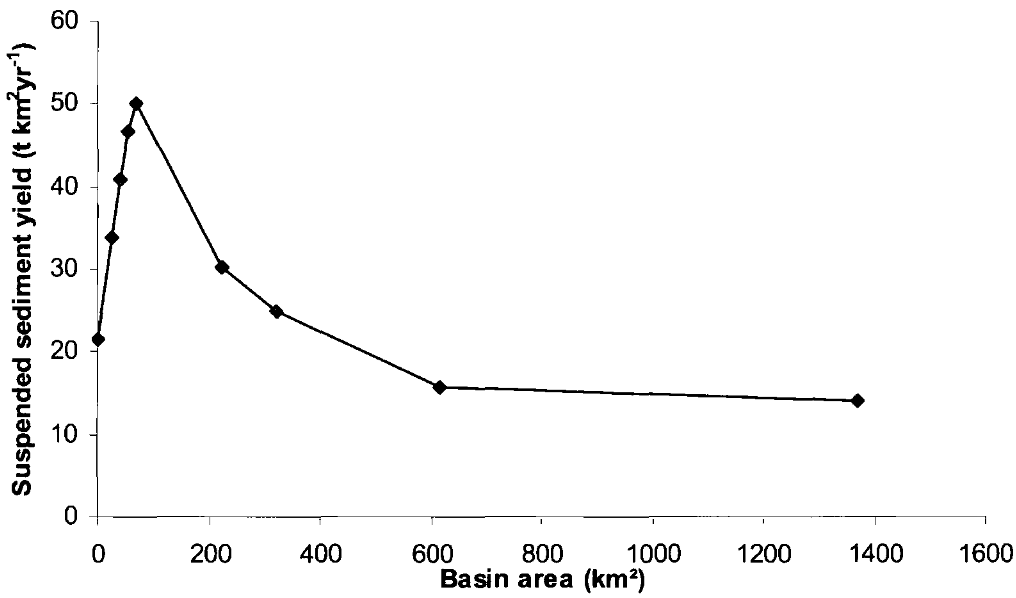

Figure 2.1. Relationship between suspended sediment yield and basin area in the Eden basin, Cumbria, UK (adapted from Bathurst *et al.*, 2005).

Catchment area and sediment yield relationships are therefore related to the land use and sediment production processes operating in different parts of a catchment. Church and Slaymaker (1989) stated that the model of an inverse relationship between specific sediment yield and catchment area was developed in small agricultural catchments and is therefore not applicable to larger undisturbed catchments. This view is supported by Dedkov (2004), who, in a study of sediment yield data from a large number of drainage basins in Eurasia, found that the relationship between suspended sediment yield and basin area was dependent on the land use intensity. Intensively cultivated basins showed a negative relationship, while undisturbed basins showed a positive relationship (Figure 2.2). An analysis of the way in which suspended sediment transport processes change downstream is useful for determining the dominant sediment input processes in different parts of a catchment, especially if coupled with a study of the river and catchment morphology, such as was carried out by Bull *et al.* (1995) and Prestegaard (1988).

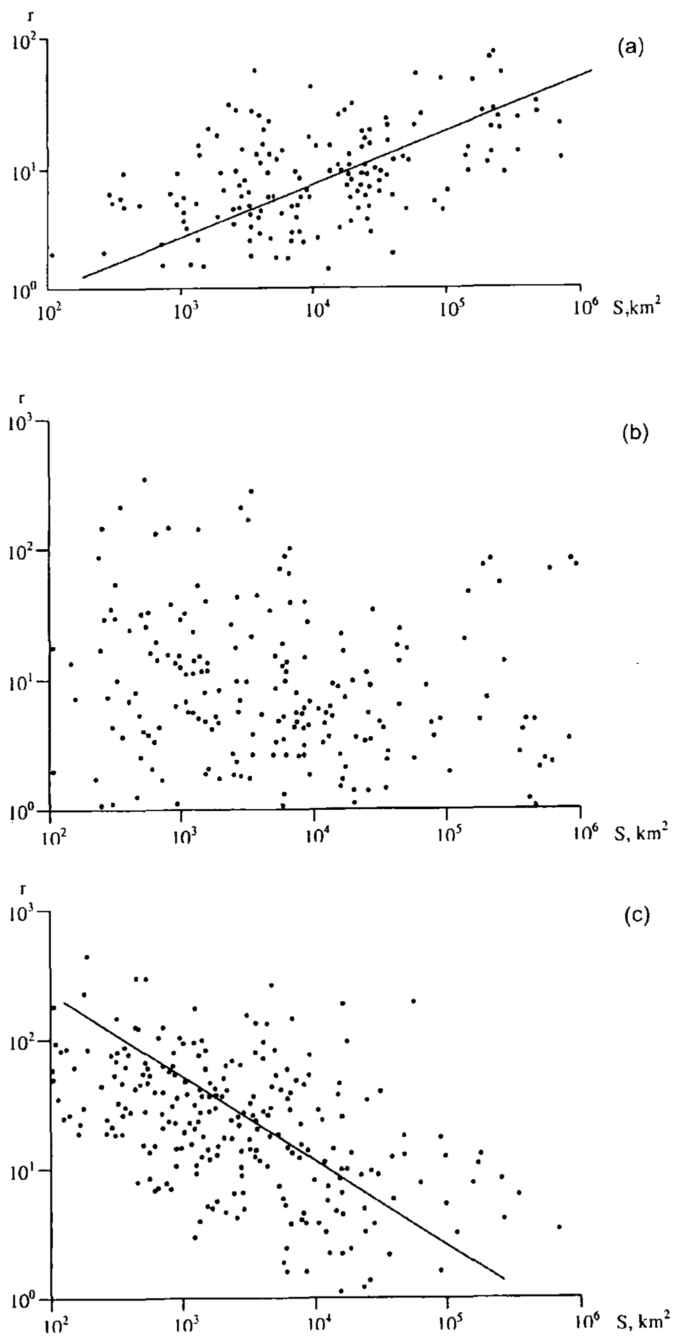

Figure 2.2. Relationships between specific sediment yield, r (t km^{-2}) and drainage basin area, S for a) uncultivated or sparsely cultivated basins, b) intermediate cultivated basins and c) intensively cultivated basins (from Dedkov, 2004).

2.2.2. Magnitude and frequency characteristics of suspended sediment load

The transport of fine sediment in rivers occurs episodically, with most sediment being transported during times of high flow, in a small proportion of the total amount of time (Loughran *et al.,* 1986; Slattery and Burt, 1996; Smith *et al.,* 2003). Table 2.1

summarises different sediment transport duration characteristics found in a range of studies.

Table 2.1. Sediment transport duration characteristics found in the literature.

Transport duration characteristic	River	Catchment area (km^2)	Length of study	Reference
79% load transported in 0.6% time	Maluna Creek, Australia	1.7	3 years	Loughran *et al.*, 1986
82% load transported in 21% time	Agricultural catchment, Oxfordshire, UK	6.2	1 year	Slattery and Burt, 1996
50% load transported in 0.35% time	Dart, UK	46	9 years	Webb and Walling, 1984
90% load transported in 20% time	Mad River, California, USA	104	31 days	Thomas, 1989
50% load transported in 0.2% time	Barle, UK	128	9 years	Webb and Walling, 1984
50% load transported in 0.8% time	Creedy, UK	262	9 years	Webb and Walling, 1984
70% load transported in 5% time	Swale, UK	1363	26 months	Smith *et al.*, 2003
50% load transported in 8% time	Murrumbidgee, Australia	82 000	42 years	Olive *et al.*, 1995

The greater capacity of the river at high flows allows for more entrainment and transport of sediment. Higher water levels enable the flow to access sediment sources on the channel banks which are normally above the water line (Hooke, 1979; Bull, 1997) and runoff in the catchment connects more distant sources of sediment to the river (Walling, 1983; Campbell, 1985). Erosion processes during a storm, due to rainfall or overland flow, may increase the sediment availability (Hicks *et al.*, 2000). Sediment load, therefore, increases non-linearly with discharge because it is related to more than just flow capacity.

This relationship means that the episodicity of sediment transport is usually greater than the episodicity of discharge (Gregory and Walling, 1973; Webb and Walling, 1984; Olive *et al.*, 1995; Smith *et al.*, 2003). This has the implication that the number of high magnitude-low frequency storm events during a period of time often has more influence on the total sediment transport over the time period than does the total discharge (Webb and Walling, 1984; Walling and Webb, 1987; Hicks, 1994; Olive *et al.*, 1995). Figure 2.3 shows that in the River Creedy, Devon, the range in suspended sediment load is greater than the range in discharge. The level of dependency of sediment yield on the occurrence of high magnitude events depends on their relative importance in transporting sediment (Hicks, 1994). The proportion of sediment which is transported above a certain discharge is dependent on thresholds for erosion, entrainment or transport of sediment in the catchment (Figure 2.4). These depend on catchment characteristics, land use and sediment availability (Webb and Walling, 1984; Walling and Webb, 1987; Hicks, 1994; Hicks *et al.*, 2000).

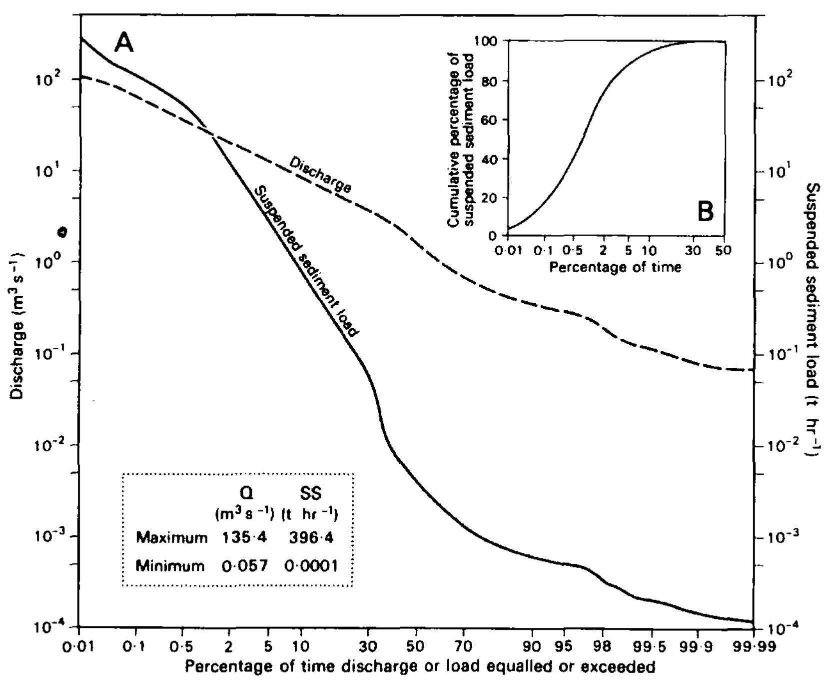

Figure 2.3. A) Duration curves of discharge and sediment load for the River Creedy, Devon, UK; B) cumulative sediment load duration curve for the Creedy (from Webb and Walling, 1984).

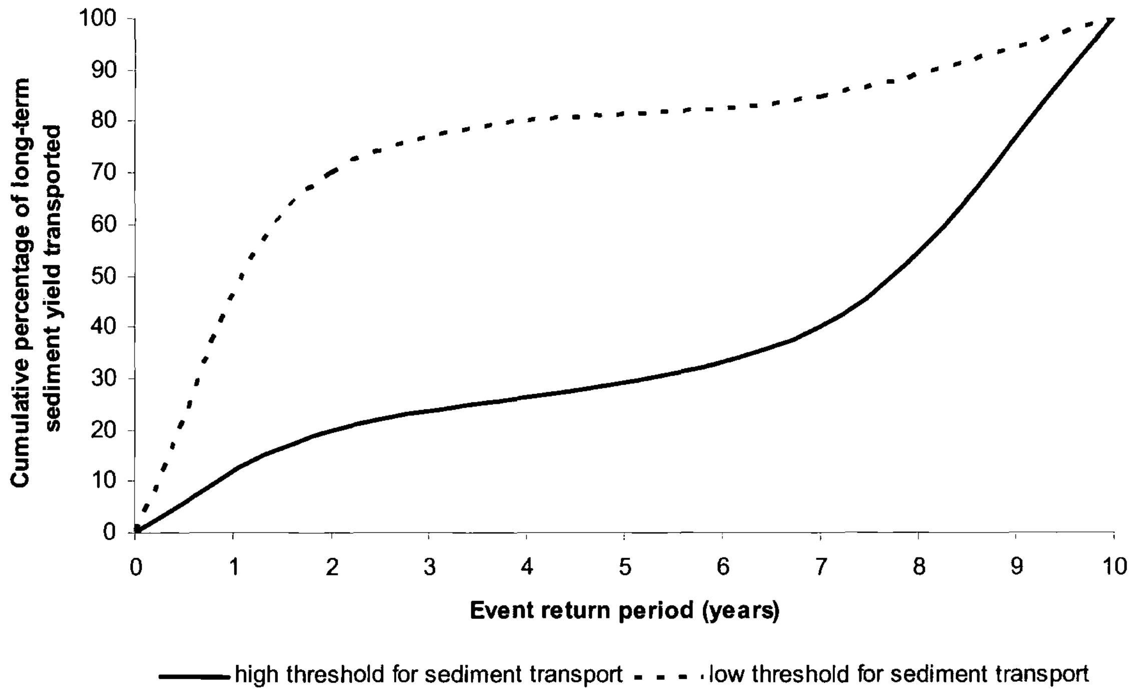

Figure 2.4. Idealised graph showing effects of different thresholds on the proportion of sediment transported by events of different magnitudes (adapted from Hicks *et al.*, 2000).

In catchments with greater sediment availability, more sediment is transported at lower discharges, whereas if more extreme events are required for access to significant sources, a higher proportion of sediment is transported at higher discharges (Webb and Walling, 1984; Hicks, 1994). For example, in a study in the Waipaoa River Basin, New Zealand, Hicks *et al.* (2000) showed that in sub-basins where most sediment was generated by landslides, more sediment was transported at higher discharges, because of a higher threshold for the initiation of landsliding. Where sediment was generated by gully erosion, events of lower magnitudes exceeded the threshold for sediment production, so a greater proportion of sediment was transported at lower discharges. Webb and Walling (1984) showed that in the River Creedy, Devon, all sediment is transported in under 50 % of the time (Figure 2.3.B).

Analysis of the sediment transport response of a catchment to runoff events of different magnitudes can help determine the relative thresholds for sediment production processes. This is of importance when investigating the sediment transport dynamics of a basin as it affects the relationship between SSC and discharge. It can also help to explain the sensitivity of the sediment transport regime in the catchment to changes in the distribution of high magnitude discharge events (due to climate change, for example), which may have important implications for future sediment yields (Longfield and Macklin, 1999).

2.2.3. Relationships between suspended sediment concentration and discharge

The way in which SSC varies with discharge during high flow events depends on whether the flux of sediment in the river is supply- or transport-limited (Olive and Rieger, 1985). Where an abundant supply of sediment is available for transport, the rate of transport is dependent on the capacity of the flow: the flux is transport limited. Where the sediment supply is less than that which the flow has the capacity to transport, so that sediment availability determines the rate of transport, flux is supply-limited. Most studies of fluvial fine sediment transport show that flux is supply-limited, because of the very high capacity of the flow to transport fine sediment (e.g. Carling, 1983; Burt and Gardiner, 1984). This is shown by the relationship between SSC and discharge, which generally incorporates large amounts of scatter (Figure 2.5) (Wood, 1977; Klein, 1984; Walling and Webb, 1987; Thomas, 1989; Jansson, 1992; Batalla and Sala, 1994; Asselman, 1999; Lenzi and Marchi, 2000; Nistor and Church, 2005), implying that discharge is not the only control over SSC. Fluvial sediment transport, therefore, depends on both the supply of sediment and the ability of the flow to entrain and transport it (Nistor and Church, 2005). This forms the basis for the interpretation of

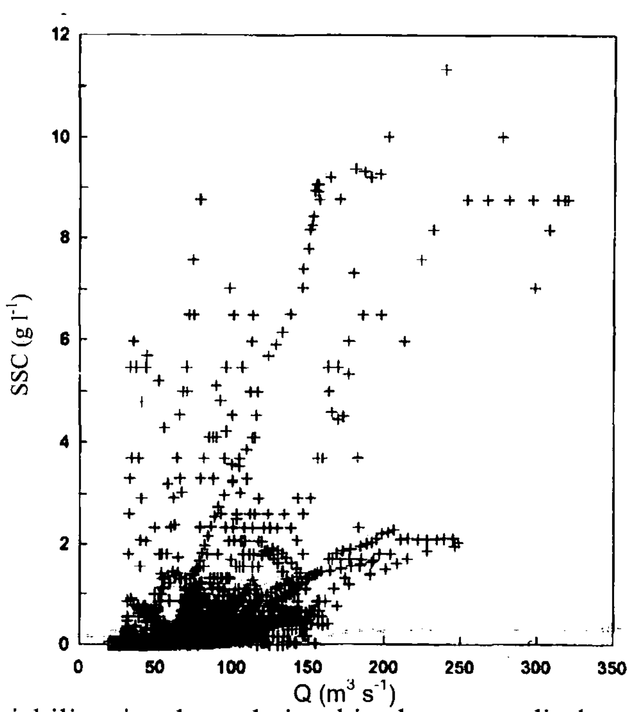

Figure 2.5. Variability in the relationship between discharge and SSC on the Reventazón River, Costa Rica, during 1990, using high frequency measurements (from Jansson, 1996).

discharge-SSC relationships, which can be used to infer sediment supply and transport dynamics in a catchment (Slattery and Burt, 1996; Seeger *et al.,* 2004).

2.2.3.1. Between-storm variability

Analysis of variations in the relationship between SSC and discharge between storms can give insight into the sediment production and supply processes in the catchment and the rates at which these occur. Sediment supply exhaustion between consecutive storms is an effect common to many studies of suspended sediment transport, whereby SSC is lower for the same, or higher, discharges in later storms (Figure 2.6) (Wood, 1977; Carling, 1983; Burt and Gardiner, 1984; Sharma *et al.,* 1984; Walling and Webb, 1987; Labadz *et al.,* 1991; Batalla and Sala, 1994; Slattery and Burt, 1996; Asselman, 1999; Nistor and Church, 2005). Periods of low flow allow replenishment of sediment sources and, consequently, high SSC during subsequent floods (Wood, 1977; Walling and Webb, 1987; Batalla and Sala, 1994; Slattery and Burt, 1996; Ziegler *et al.,* 2001).

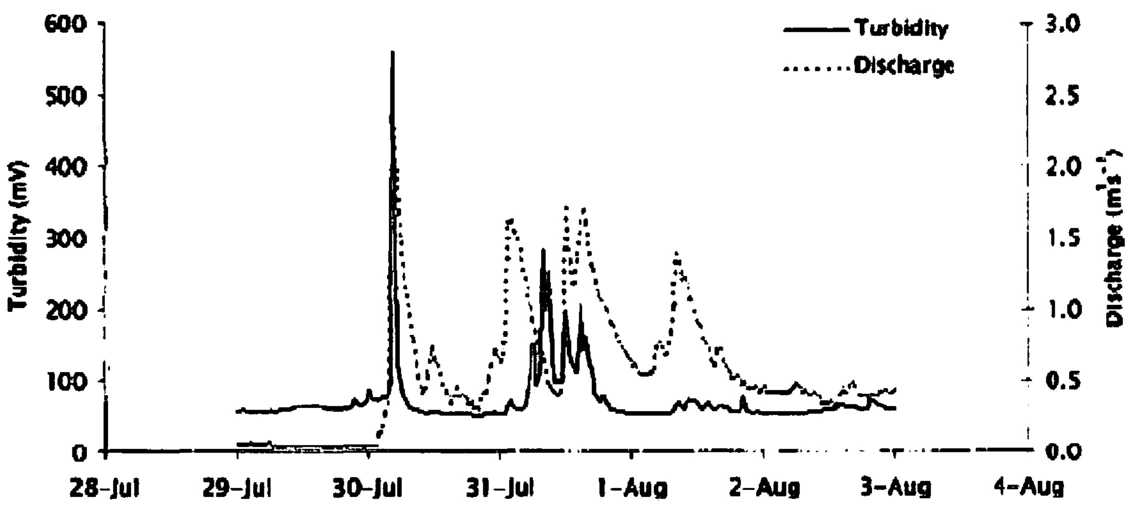

Figure 2.6. Sediment depletion during four successive storms on the Bore Khola, Nepal, during the 1992 monsoon (from Brasington and Richards, 2000).

The amount of sediment transported in an individual event may, therefore, depend on the amount of time since a preceding event, since this dictates the length of time available for the operation of sediment production processes and the amount of sediment available for transport (Carling, 1983; Smith and Olyphant, 1994; Asselman, 1999; Couper and Maddock, 2001; Ziegler *et al.,* 2001). The distribution of sediment recharge events, such frost action, between storms may also be important in dictating the amount of sediment transported in a particular storm (Nistor and Church, 2005). The implication of this is that the total amount of sediment transported out of a catchment over a period of time is dependent not only on the magnitude of storms, but also on the timing of storms in relation to the available sediment supply. For example, if most of the rainfall occurred during a single large event, sediment exhaustion might limit the total amount of sediment transported. If, however, rainfall events were spaced out to allow replenishment of sediment supplies between events, the total amount of sediment transported would be likely to be greater (Smith and Olyphant, 1994).

The amount of time since a preceding event can also affect inter-storm variability in sediment supply and transport through its influence on catchment wetness (Finlayson, 1978; Carling, 1983; Olive and Rieger, 1985; Armstrong, 2005). The catchment is likely to be wetter if a storm occurred recently. Wetter catchments have greater connectivity between sediment sources and the river (Seeger *et al.*, 2004), allowing the input of distant as well as local sources. In this case, the length of time since a preceding storm has the opposite effect on sediment availability. The system response must, therefore, depend on the relative influences of catchment wetness and sediment exhaustion on sediment supply.

The effects of seasonality of land use and vegetation type can cause inter-storm variability in suspended sediment yields (Jeje *et al.*, 1991; Batalla and Sala, 1994; Smith *et al.*, 2003), since different land uses are often associated with different sediment sources or sediment production processes, which interact with rainfall and discharge in different ways (Ichim *et al.*, 1984; Beschta, 1987). For example, Brasington and Richards (2000) showed sediment transport in the Middle Nepal Hills became more supply-limited as the monsoon progressed, because of the growth of vegetation which reduced the amount of bare, loose sediment. Soil disturbance related to cultivation on hillside terraces also introduced seasonal patterns to the suspended sediment regime in their study. Lenzi and Marchi (2000) showed seasonal differences in suspended sediment transport patterns due to the different effects of rainfall and snowmelt on sediment entrainment and transport in a small stream in the Italian Dolomites.

Studies of between-storm variability in suspended sediment transport highlight the importance of supply conditions in dictating the suspended sediment transport patterns of a storm. Antecedent conditions in the catchment are of great importance in determining the available sediment supply (Smith *et al.*, 2003; Nistor and Church, 2005). The concept of 'system memory' describes this effect, whereby the patterns of processes operating are determined by the antecedent conditions in the catchment, as well as contemporary conditions (Bogen, 1980). The range of investigations discussed above also highlights the number of complex combinations of sediment transport and supply processes in operation in catchments. Approaches such as those of Brasington and Richards (2000) and Nistor and Church (2005) which investigate catchment processes as well as suspended sediment dynamics, are needed to help unravel the causes of particular suspended sediment patterns.

2.2.3.2. Within-storm variability

Variations in the relationship between SSC and discharge within storms are common and can be used to infer sediment input mechanisms during high flow events. Hysteresis loops are a common characteristic of within storm discharge-suspended sediment relationships (Wood, 1977; Bogen, 1980). They are produced either by a lagged response of one variable, or by an asymmetric response of the two variables (Prowse, 1984), so that a different SSC occurs for equivalent discharges in different parts of the storm. Part of the difference in the response of discharge and SSC may be explained by energy dissipation in the system, which causes the sediment wave to lag behind the water wave. This is referred to by Prowse (1984) as 'true hysteresis' and can only occur in an anticlockwise direction. Other variations in response are due to differences in sediment supply and transport processes (Prowse, 1984). The inconsistent relationship between discharge and SSC implies that sediment supply, rather than discharge, is the dominant control on SSC. The nature of the hysteresis loop depends on the dynamics of the supply. For example, Brasington and Richards (2000) found that in the Middle Nepal Hills the high variation in sediment source areas between storms caused a high variability in the type of hysteresis. Several authors have attempted to classify hysteresis loops into certain types (e.g. Wood, 1977; Klein, 1984; Olive and Rieger, 1985; Williams, 1989; Nistor and Church, 2005; Armstrong, 2005). The most common ones are illustrated in Figure 2.7.

Williams (1989) used the ratio between sediment concentration and discharge on the rising and falling limbs to analyse hysteresis loops quantitatively. For a single-valued line or curve (Figure 2.7 D), the C/Q ratio is equal for all equal values of Q. This occurs where water and sediment concentration have simultaneous peaks and the same skewness. Differences in the spread of the two variables results in a curved line. A clockwise loop (Figure 2.7 A) would have a greater C/Q ratio on the rising limb than for an equivalent value of Q on the falling limb, while an anticlockwise loop (Figure 2.7 B) would have a greater C/Q ratio on the falling limb. A hysteresis loop may result even if the two peaks occur simultaneously, but the curves have different amounts of skewness. The size and shape of the loop depends on the relative sizes and shapes of the sediment concentration and water discharge curves. A greater amount of offset between the two curves results in a wider loop. All other types of loop, such as multiple loops (Figure 2.7 C) or figure of eight loops are a combination of one or more of the basic types described above.

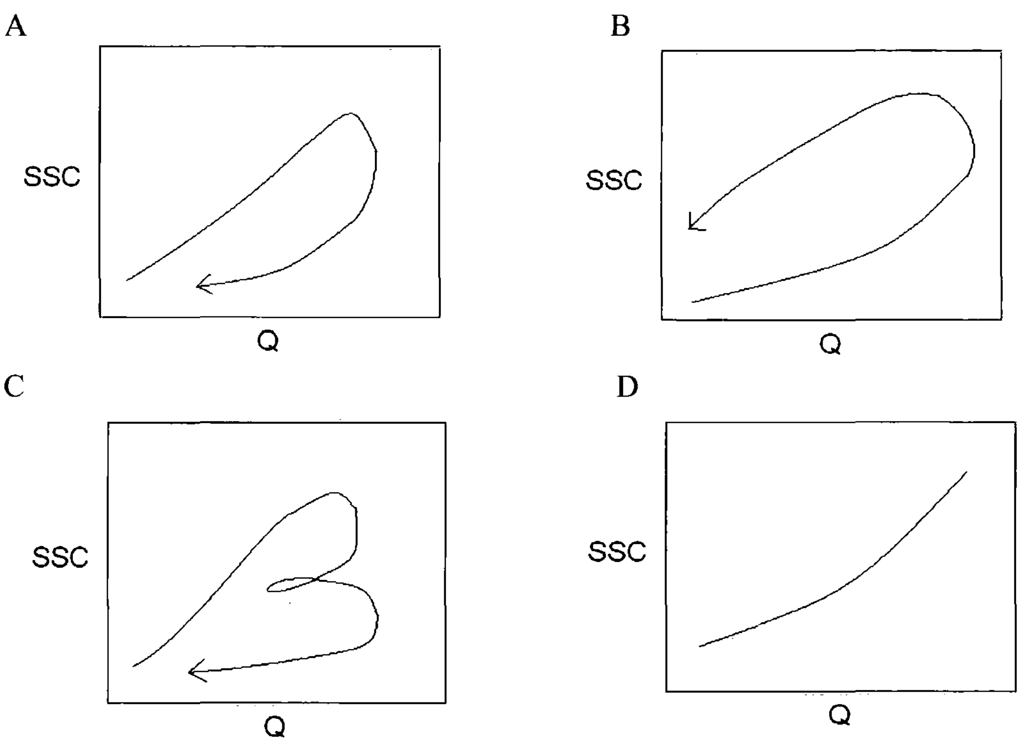

Figure 2.7. Idealised plots of suspended sediment-discharge relationships. A) clockwise hysteresis; B) anticlockwise hysteresis; C) multiple clockwise hysteresis loops; D) simple curve (adapted from Nistor and Church, 2005).

Lawler *et al.* (2006) devised a hysteresis index to quantify the magnitude and direction of hysteresis by calculating the difference between the rising and falling limb values of turbidity or SSC as follows for a clockwise loop:

$$HI_{mid} = (TU_{RL} / TU_{FL}) - 1 \qquad \text{(Equation 2.1)}$$

or for an anticlockwise loop:

$HI_{mid} = (-1/(TU_{RL}/TU_{FL})) + 1$ (Equation 2.2)

where HI_{mid} is the hysteresis index for the midpoint discharge and TU_{RL} and TU_{FL} are the rising and falling limb values of turbidity respectively, at the median discharge, Q_{mid}. A higher HI_{mid} value indicates a greater hysteresis effect, while HI_{mid} values are positive for clockwise hysteresis and negative for anticlockwise hysteresis. This provides a simple method for analysing hysteresis patterns

Clockwise hysteresis (Figure 2.7.A) is the most common type reported in studies of suspended sediment transport (Collins, 1981; Carling, 1983; Beschta, 1987; Jeje *et al.*, 1991; Labadz *et al.*, 1991; Lenzi and Marchi, 2000; Picouet *et al.*, 2001; Seeger *et al.*, 2004; Armstrong, 2005) and indicates higher SSC on the rising limb than on the falling limb for an equivalent discharge (Nistor and Church, 2005). Several reasons have been cited to explain the occurrence of clockwise hysteresis. A common reason is the depletion of the sediment supply during the storm event. This may involve depletion of within channel sources (Gilvear and Petts, 1985; Batalla and Sala, 1994; Slattery and Burt, 1996; Jansson, 2002) or catchment sediment sources (Burt and Gardiner, 1984; Olive and Rieger, 1985; Froehlich, 1991; Jeje *et al.*, 1991; Smith and Olyphant, 1994) during a storm. Collins (1981) suggests that flows in smaller catchment areas are more likely to exhibit clockwise hysteresis because sources are close to the channel so will arrive almost immediately during a storm. However this is not always the case, as demonstrated by Klein (1984), who showed anticlockwise hysteresis in a catchment of only 0.5 km^2 in Yorkshire.

A reduction in the erosivity of rainfall during the storm is also a cause of clockwise hysteresis (Sharma *et al.*, 1984; Jeje *et al.*, 1991; Jansson, 2002), because fewer hillslope sediment sources are able to become entrained later, reducing the sediment supply towards the end of the hydrograph. Clockwise hysteresis has also been attributed to a local supply of sediment, which becomes diluted by the later arrival of water with a low sediment concentration from more distant parts of the catchment (Jansson, 2002), or from baseflow (Picouet *et al.*, 2001; Jansson, 2002). Similarly it may occur due to differences in the timing of the arrival of water of different concentrations from different tributaries (Asselman, 1999).

Anticlockwise hysteresis (Figures 2.7.B and 2.8) is less commonly observed than clockwise hysteresis (e.g. Klein, 1984; Brasington and Richards, 2000). Anticlockwise hysteresis indicates that sediment concentrations are higher during the later stages of a hydrograph, implying an input of sediment late in the storm. This may be because dominant inputs during a storm are from lower velocity hillslope flow, as opposed to more rapid channel flow (Klein, 1984). Brasington and Richards (2000) attributed anticlockwise hysteresis in the Middle Nepal Hills to a faster rate of travel of water through the system than sediment, causing the later arrival of sediment downstream during the storm. This effect may have been exacerbated by the presence of step-pool channels which attenuate sediment transport. If sediment sources are from more distant parts of the catchment, such as from hillslope failures, overgrazed areas or from a particular tributary, anticlockwise hysteresis may result, due to the longer travel time of sediment compared to runoff (Klein, 1984; Loughran *et al.,* 1986; Asselman, 1999; Lenzi and Marchi, 2000). Klein (1984) used a simple model (Figure 2.9) to conceptualise the relationship between travel times and hysteresis direction in a small catchment. The collapse of river banks on the falling limb of hydrographs is a commonly observed phenomenon (Jeje *et al.,* 1991; Thorne, 1997; Rinaldi *et al.,* 2004) causing a late input of suspended sediment during a storm and, hence, anticlockwise hysteresis (Carling, 1983; Armstrong, 2005).

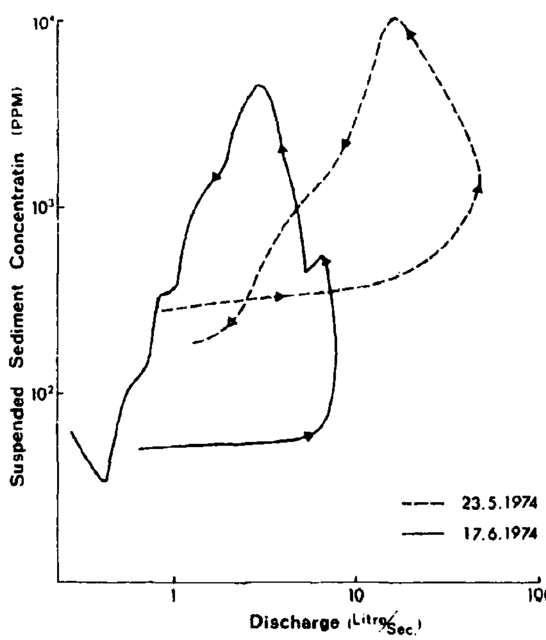

Figure 2.8. Examples of anticlockwise hysteresis in the Holbeck catchment, Yorkshire, UK (from Klein, 1984).

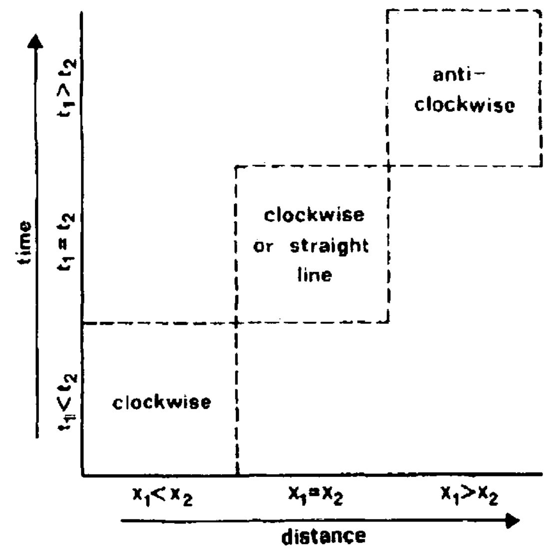

Figure 2.9. Model to predict hysteresis type from the relative locations of the main sediment and water contributing areas. x_1 – distance from sediment source area to basin outlet; x_2 - distance from water contributing area to basin outlet; t_1 – travelling time of sediment to basin outlet; t_2 – travelling time of water to basin outlet (from Klein, 1984).

In some studies anticlockwise hysteresis is observed in a small number of storms in a catchment otherwise dominated by clockwise hysteresis. This may indicate the operation of a different sediment input mechanism. It is commonly associated with storms of long duration, or high antecedent catchment wetness (Jeje *et al.,* 1991; Seeger *et al.,* 2004; Armstrong, 2005). This is thought to be because greater catchment wetness allows the connection of distant sources with a greater travel time to the main river and because these additional sources reduce the sediment exhaustion effect normally seen (Seeger *et al.,* 2004; Armstrong, 2005). Armstrong (2005) also attributed anticlockwise hysteresis to the late arrival of sediment triggered by an upstream storm, or to the retention of sediment by debris in the channel, which could only be moved above a certain discharge. Jeje *et al.,* (1991) also suggest the collapse of log jams as a reason for anticlockwise hysteresis in a Nigerian river. In a study of a semi-arid drainage basin in Alberta, Canada by de Boer and Campbell (1989), the occurrence of anticlockwise hysteresis was found to indicate that tunnel flow in the underlying shales had been initiated and was contributing a later input of sediment during the event.

Multiple or complex hysteresis loops (e.g. Figure 2.7.C) are often associated with storms of longer duration with a more complex discharge pattern (Collins, 1981), which have the capacity to mobilise a greater number of different sources in a catchment (Jeje *et al.*, 1991; Armstrong, 2005). Multiple loops may occur during multiple hydrograph rises, with a sediment peak associated with each hydrograph peak (Olive and Rieger, 1985; Nistor and Church, 2005). In this situation each successive discharge peak often has a lower sediment peak, due to exhaustion of sources during the storm (Olive and Rieger, 1985; Nistor and Church, 2005). Sediment inputs may also occur independently of hydrograph rises (Nistor and Church, 2005). If there are several different sediment sources in a catchment, or different sediment transfer processes operating, sediment peaks may occur at several times during a storm, causing complex hysteresis (Jeje *et al.*, 1991; Armstrong, 2005).

Figure-of-eight loops have been observed by Lenzi and Marchi (2000) and by Seeger *et al.* (2004) in the Spanish Pyrenees. The initial clockwise loop was thought to be due to the rapid entrainment of near-channel sources at the beginning of a storm. The subsequent anticlockwise loop was caused by the later input of more distant sources, due either to increasing catchment saturation and therefore connectivity during the storm (Seeger *et al.*, 2004) or because of the longer travel time for these sources to reach the stream (Lenzi and Marchi, 2000). Random behaviour of SSC during discharge peaks has been observed in New South Wales by Olive and Rieger (1985) and in Nigeria by Jeje *et al.*, (1991) and reflects a large number of different sediment sources and sediment generating processes operating during a storm.

A non-hysteretic response, where suspended sediment transport is correlated to runoff volume (Figure 2.7.D) was observed by Wood (1977) in short duration storms which did not exhaust sediment supplies in the River Rother, West Sussex. It was also observed by Olive and Rieger (1985) and by Nistor and Church (2005) at high volumes of runoff in small catchments in New South Wales and British Colombia respectively. In these situations sediment transport is not supply limited, possibly because the higher shear stresses created by the runoff volumes exceeded the threshold needed to move larger debris, more stored sediment was able to be accessed because of the higher water levels and extreme rainfall led to the occurrence of more sediment-generating events. Similarly, Burt and Gardiner (1984) found SSC and discharge were closely related in runoff from an eroding peat catchment because the supply of sediment was continually replenished during the storm, due to the erosive action of rainfall on bare peat.

The above discussion shows that the shape of the SSC discharge relationship is determined by a large number of factors in the catchment, important ones being the availability, location and nature of the sediment supply. Interpretation of hysteresis loops alone cannot determine the sediment sources to the river, because of the large number of situations which could cause a hysteresis loop of the same shape (Slattery and Burt, 1996; Jansson, 2002). Knowledge of hysteresis patterns combined with reconnaissance of catchment sources and processes can be very effective in determining the dominant sediment supply processes operating (e.g. Brasington and Richards, 2000).

2.3. Processes causing inputs of fine sediment to fluvial systems

From the literature already reviewed it has been established that the patterns of suspended sediment flux observed in a river are determined both by the flow and by spatial and temporal variation in the supply of sediment to the river. The variation of SSC with discharge can be used to infer dominant processes causing sediment input to the fluvial system. It is important, therefore, to understand how potential sediment input processes behave. Sources can be divided into those occurring in the catchment and those in the channel itself. A brief review of the behaviour of these sources in catchments similar to that of the Esk follows.

2.3.1. Non-channel sources

The rate of delivery of sediment from the catchment to the river is dependent on the rate of sediment production in the catchment and the level of connectivity between the sediment source and the channel (Walling, 1983; Warburton *et al.*, 2003). In Britain the areas of the landscape most sensitive to erosion are areas of arable cultivation. Well established and relatively undisturbed areas of grassland, heath, moor and improved grassland (such as are found in the Esk catchment) are less sensitive to erosion (Evans, 1993). There are several mechanisms of sediment production in upland areas. On peat and rough grassland mass movement may occur during large storm events in the form of debris flows and landslides which supply sediment to local watercourses. Drainage ditches in upland moors are another cause of sediment production, especially when widened by subaerial and fluvial erosion processes and by livestock (Evans, 1993).

High grazing intensities have been shown to initiate soil erosion and to exacerbate existing soil erosion, particularly in areas of peat (Evans, 1997). Heathwaite *et al.* (1990) found that surface runoff quantities and SSC were higher from heavily grazed and trampled areas of pasture in a rural catchment in southwest England. Where pasture occurs adjacent to the channel, poaching of channel banks by livestock may significantly increase sediment input into the river (Heathwaite *et al.*, 1990; Gruszowski *et al.*, 2003).

The relative importance of sediment sources in the catchment for fluvial sediment supply depends on whether they are connected with the channel. Storage of sediment at the base of slopes, behind barriers and on the floodplain prevents eroded sediment reaching the channel (Walling, 1983). Evans and Warburton (2005) showed that despite high rates of hillslope erosion, poor connectivity between sediment sources and the channel reduced the importance of these, in comparison to within-channel sources, in the sediment budget of a small upland catchment in the north Pennines. Connectivity and sediment delivery in a catchment is temporally variable and related to antecedent soil moisture conditions (Walling, 1983). As discussed in Section 2.2.3.2, the common occurrence of anticlockwise hysteresis following high levels of antecedent precipitation demonstrates the greater connectivity and input of sediment from more distant parts of the catchment when the catchment is wetter. Connectivity in the catchment may also be enhanced by features such as roads, ditches and drains, which provide efficient pathways for sediment transfer (Russell *et al.*, 2001; Ziegler *et al.*, 2001; Gruszowski *et al.*, 2003).

2.3.2 In-channel sources

In catchments, such as the Esk, which are relatively undisturbed, channel sources usually contribute to a high proportion of the suspended sediment load. Babtie Brown & Root and Environment Agency (2004) consider channel sources to be an important component of the suspended sediment supply to the Esk.

2.3.2.1. Bank erosion

Bank erosion occurs through a number of different processes. The intensity and relative importance of each process affects the dynamics of sediment supply to the river and therefore exerts an important control over rates of suspended sediment flux. Bank erosion processes include subaerial activity, such as freeze-thaw weathering and desiccation, fluvial erosion and mechanical bank failure processes, such as slumping and toppling (Thorne, 1997). Although many studies have attempted to determine the main bank erosion processes operating and their influencing factors, few have then related this to the dynamics of sediment flux.

Direct fluvial entrainment from the bank face or from accumulated material at the base of the bank is responsible for increases in SSC at high flows (Bull, 1997). The rate of fluvial entrainment depends on the shear stress of the flow, the resistance of the bank material and the degree of sub-aerial preparation of the material (Knighton, 1973; Ashbridge, 1995; Thorne, 1997). Mechanical failure of river banks commonly occurs during the falling stages of a flood hydrograph (Ashbridge, 1995; Thorne, 1997; Rinaldi *et al.,* 2004). This is thought to be due to a reduction in bank shear strength caused by wetting of the bank, accompanied by a loss of confining support from flow following drawdown (Rinaldi *et al.*, 2004). It has been observed that higher rates of bank retreat occur in association with multi-peaked floods, due to the weakening effect of constant rewetting (Knighton, 1973; Rinaldi *et al.*, 2004). Bank failure on the falling limb of the hydrograph has been cited as a cause of anticlockwise hysteresis (e.g. Armstrong, 2005). It may also result in the deposition of bank material in the channel which is not immediately entrained due to reduced flow competence, but is temporarily stored and is then available to supply material to subsequent floods (Ashbridge, 1995; Bull, 1997).

Inter-storm operation of subaerial processes is likely to reduce the threshold of stability of the bank, making it more susceptible to erosion by high flows (Knighton, 1973; Couper and Maddock, 2001). Therefore bank retreat rates are not necessarily correlated to discharge magnitude, but are more complexly linked to the operation of various subaerial processes (Hooke, 1979; Lawler, 1986; Couper and Maddock, 2001). It is a combination of flow events and preparation processes which cause bank erosion and highest rates will be found when these combine to produce optimum conditions. In many systems these conditions occur at certain times of year and result in a seasonal pattern of bank erosion, and therefore sediment supply to the river (e.g. Lawler, 1986; Ashbridge, 1995; Bull, 1997; Lawler *et al.,* 1999; Couper and Maddock, 2001).

2.3.2.2. In-channel sediment storage

Storage of fine sediment in river channels provides a source of sediment during high flow. Lisle and Hilton (1999) found that sediment stored in pools of a gravel bed river was subject to frequent scour and fill, suggesting that this is an important contribution to the load of the river. According to Owens *et al.* (1999) storage of sediment in the channel accounts for 4% of the annual fine sediment budget of the River Tweed. However, the dynamics of fine sediment storage in river channels are little understood and comparatively under-researched, which is surprising considering their potential implications for sediment yields and for flow-SSC relationships. Part of the reason for the lack of study of in-channel fine sediment storage can be attributed to difficulty in developing representative sampling and measuring techniques (Lambert and Walling, 1988; Zimmermann *et al.,* 2005). Techniques which have been adopted include bed sediment traps (Acornley and Sear, 1999; Walling and Amos, 1999), agitation of the bed (Wilson *et al.,* 2004) and freeze-coring (Zimmerman *et al.*, 2005).

The storage of fine material in the channel bed is dependent on the supply of fine material to the channel; the capacity for this sediment to infiltrate the bed gravels determines whether it is stored within the bed matrix, or as a deposit on the surface (Lisle and Hilton, 1999). Sediment stored on the bed surface is exposed to the flow and is therefore highly mobile compared to sediment stored within the bed, which is protected by the surface gravels and is only accessible to the flow during bed-mobilising discharges (Acornley and Sear, 1999). The capacity for fine sediment to infiltrate the gravel bed is dependent on the relative sizes of the bed sediment and the fine sediment. Lisle (1989) found that overlap between the size ranges of the sediments often resulted in fine sediment infiltrating only a small way into the bed. This then blocked further infiltration of fine sediment. It was also found that the bed was more susceptible to infiltration by fine bedload than by suspended sediment because of the more frequent contact of this size range with the bed.

The contribution of the fine sediment stored in the bed to the suspended load varies between rivers. Seasonally high SSC values, but stable flows and lack of flushing, caused net accumulation of fine sediment in the bed gravels in a gravel bed channel in southern England (Acornley and Sear, 1999). In contrast, a study on the River Exe, (Lambert and Walling, 1988) concluded that little bed storage of sediment occurred and that which did occur contributed little to the suspended sediment load; most sediment was conveyed rapidly through the system. In a comparison of reaches in four medium-scale rivers in southwest England, Wilson *et al.*, (2004) found no relationship between volumes of sediment storage and rates of suspended sediment transport. In contrast, significant sediment storage in the gravel-bed channel of the River Piddle in Dorset was found by Walling and Amos (1999), which exerted a strong influence on the suspended sediment dynamics of the system. A seasonal flushing of sediment through the system during winter storms was observed. These varied results suggest that the controls on the volume and distribution of bed storage of suspended sediment and its contribution to the suspended load are complex.

The storage and transfer of sediment in the fluvial system is likely to be affected by features within channels which prevent the free movement of sediment taking place. Babtie Brown & Root and Environment Agency (2004) note the occurrence of point storage of sediment in the upper Esk catchment, due to in-channel features such as bridges, weirs, large woody debris, dams and fords (Figure 2.10). Jeje *et al.* (1991) and Armstrong (2005) both suggest that anticlockwise hysteresis may result from the accumulation of sediment behind debris in the channel, which is only released when debris blockages are removed at high discharges. Again, little work has been undertaken to try and quantify the volume and processes of point storage within river channels, and the effect that these might have on the suspended sediment load.

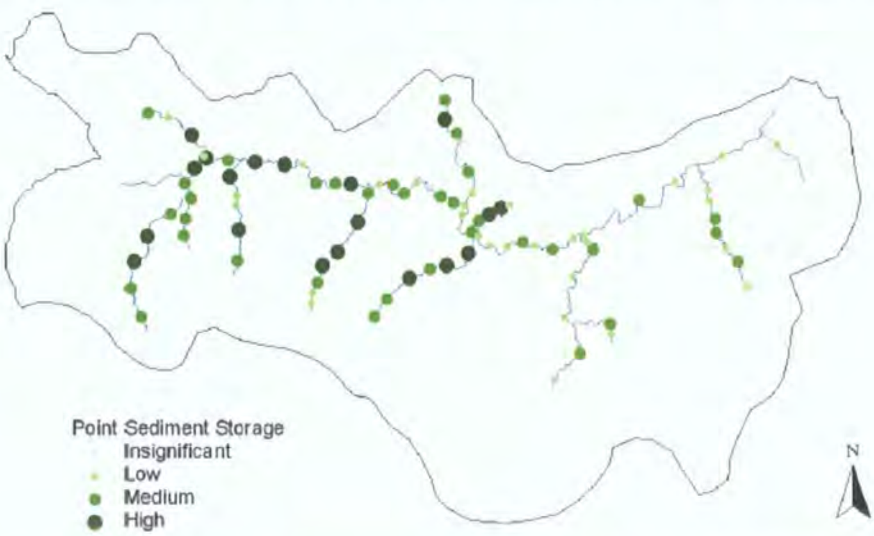

Figure 2.10. Areas of point sediment storage in the Esk and its tributaries (from Babtie Brown & Root and Environment Agency, 2004).

Lisle and Hilton (1999) show the importance of pools and areas of low shear stress as areas for the deposition and storage of fine gravel and sand, and the susceptibility of these surficial deposits for entrainment during subsequent high flows. A number of authors including Keller and Swanton (1979), Mosley (1981), Hickin (1984), Montgomery *et al.* (1996) and Massong and Montgomery (2000) show the large influence that debris blockages can have on sediment storage in channels by causing deposition of alluvial material and reducing the rapidity of downstream sediment transport. Thus, log and vegetation jams are likely to influence rates and patterns of movement of suspended sediment through the channel (Figure 2.11). The importance of sediment storage caused by large woody debris depends on the size and density of available wood, the capacity of the stream to remove wood (Gregory, 1992; Massong and Montgomery, 2000) and the frequency of log jams relative to the occurrence of other storage features such as point bars and riffles (Keller and Swanton, 1979).

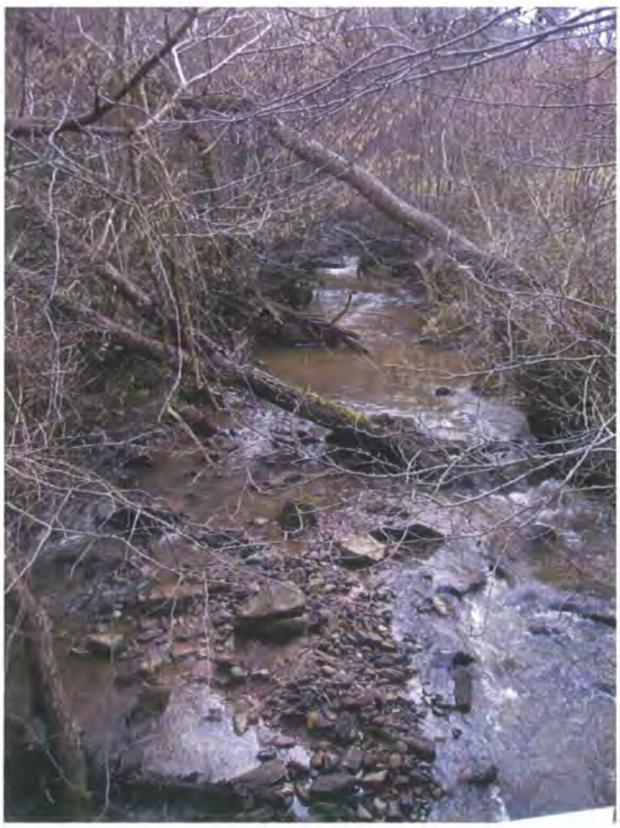

Figure 2.11. Debris in Butter Beck, a tributary of the river Esk, Yorkshire, UK.

2.4 Summary

The literature reviewed in this chapter has demonstrated the high spatial and temporal variability in suspended sediment loads and concentrations. Analyses of suspended sediment dynamics within and between storms give insight into the processes operating to supply sediment to the system. The concepts of supply- and transport-limited sediment flux underpin the analysis of suspended sediment dynamics. Most transport is supply-limited, which leads to another important concept: that of antecedent conditions, or system memory, whereby previous conditions in a catchment affect the supply of sediment available to a subsequent storm and therefore the sediment transported during the event. The tendency for most fine sediment to be transported at high discharge means that the magnitude and frequency characteristics of storm events are an important concept in the analysis of patterns of sediment flux. They affect patterns of sediment transport on an inter-storm scale by affecting the temporal dynamics of sediment supply and recharge, and on an inter-annual scale because of their effect on sediment loads. The analysis of SSC-discharge relationships and hysteresis loops can be used to infer the operation of certain sediment transfer processes and is particularly effective when combined with catchment reconnaissance.

The level of understanding of the way in which catchment processes result in sediment input into fluvial systems varies according to the process being studied; the wide variation both within and between catchments means that there is much scope for further work. This chapter has particularly highlighted the need for a better understanding of how fine sediment stored in channels affects fine sediment dynamics at inter-and intra-storm timescales and, to a lesser extent, the way in which bank erosion processes affect within storm suspended sediment hysteresis.

3. Methodology

3.1. Introduction

This chapter describes the methods employed in this study. This is preceded by a brief review of the suspended sediment measurement techniques employed in previous research. The episodic nature of suspended sediment flux and lack of a strong relationship with discharge means that careful design of sampling strategies is necessary in order to obtain a representative and accurate measurement of suspended sediment flux.

3.2. Measuring suspended sediment flux

3.2.1. River water sampling

Sampling of river water can provide a direct measurement of SSC at a single point in time and space. However, as SSC varies greatly, both temporally and spatially, a large number of water samples are needed in order to gain a fully representative picture of the suspended sediment flux in a river (Walling, 1977; Johnson, 1992; Phillips *et al.,* 1999). As discussed in Chapter 2, a large proportion of the suspended sediment transport in a river occurs during high flow events which occupy a small proportion of the time. This is particularly the case in small headwater catchments (Johnson, 1992). A water sampling programme which takes samples at regular but infrequent intervals (e.g. weekly, fortnightly or monthly) is unlikely to sample over a full range of discharge and SSC values and is therefore liable to under- or over-predict loads (Walling, 1977; Walling *et al.,* 1992, Phillips *et al.,* 1999). If possible, suspended sediment sampling strategies should be designed to take frequent samples at high flows. This can be done by using an automatic pump sampler which is triggered by a float switch to take a set of samples at high discharges (e.g. Holliday, 2003; Armstrong, 2005).

Random sampling is desirable if a sampling strategy is to be unbiased and for a valid estimate of sample variance to be made (Thomas and Lewis, 1993). Thomas and Lewis (1993) show that random sampling, but with manageable sample sizes, can be accomplished by employing a stratified sampling strategy, with a pre-specified number of samples being taken randomly in each stratum. The sediment load estimated for each stratum can then be added to give total load (Thomas and Lewis, 1993; 1995). Ideally strata should be based on SSC variation, but since this is unknown at the time of sampling they can be defined from an auxiliary variable, such as stage (Thomas, 1985). Sampling suspended sediment within strata enables sampling densities to be altered at different flow stages, it ensures all parts of the hydrograph are sampled and by sampling within a relatively homogeneous population, variance is reduced, thereby increasing the quality of load estimates (Thomas and Lewis, 1993). However, the success of the strategy is dependent upon the ability of the hydrologist to define suitable strata or a reliable auxiliary variable.

The concentration of suspended sediment is frequently variable within a river cross section, especially for sediment with larger grain sizes, the transport of which is more dependent on flow velocity distribution (Horowitz *et al.*, 1989). A single sample is unlikely to be representative of the mean cross-sectional value and may introduce bias (Horowitz *et al.*, 1990; 1992). Sampling strategies should take into account the way in which suspended sediment varies within the cross-section by employing depth and width integrated sampling. However, depth and width integrated sampling is time-consuming and cannot be employed at a high temporal resolution (Horowitz *et al.*, 1990). In order to improve the reliability of samples Horowitz *et al.* (1992) calculated regression relationships with R^2 values of over 0.98 between SSC estimates from cross-section integrated samples and point samples in the Askansas and Chattachoochee Rivers in the USA. This enabled cross-section integrated suspended sediment values to be reliably predicted from point measurements, as long as the regression relationship had been constructed for over 90% of the hydrograph, and was site-specific.

In a different study Gurnell *et al.* (1992) showed that in a Swiss proglacial river SSC varied randomly around a cross-sectional mean (apart from at the very edges of the channel, which had a lower concentration). This led Gurnell *et al.* (1992) to believe that suspended sediment was well-mixed in this river, so that an unbiased sample of suspended sediment from a cross section could be obtained from random sampling. The degree to which suspended sediment is mixed within a cross section is, therefore, dependent on the nature of the river.

3.2.2. Sediment rating curves

In order to predict suspended sediment loads using infrequent samples, a rating curve may be calculated by a regression of SSC against discharge values (Olive and Rieger, 1992). The simplest form of a rating curve is:

$$C = aQ^b \qquad \text{(Equation 3.1)}$$

where C = SSC and Q = discharge.

The often weak relationship between discharge and SSC (discussed in Chapter 2) (e.g. Figures 2.5 and 3.1) results in uncertainty in the suspended sediment loads calculated using rating curves (Wood, 1977; Thomas, 1989; Picouet *et al.*, 2001). This is especially the case where the relationship is extrapolated beyond the sampled range, as the SSC-discharge relationship is often non-linear (Fenn *et al.*, 1985; Olive and Rieger, 1992). It must also be taken into account that rating curves calculated using measurements from a short time period may not be fully representative of a system in which seasonal and annual variability is commonplace (Fenn *et al.*, 1985; Olive and Rieger, 1992; Jansson, 1996; Asselman, 2000). The reliability of rating curves can be improved by separating sediment concentration data into separate populations and using a different curve for each (Figure 3.1) (Walling, 1977; Fenn *et al.*, 1985; Armstrong, 2005), as suspended sediment behaviour often varies seasonally, or in relation to hydrograph limb (discussed in Chapter 2).

The wide use of the rating curve shows that, despite its problems, it is a useful tool for the calculation of suspended sediment loads. A more detailed study of suspended sediment behaviour, however, requires the closer analysis of SSC variations and the consideration of a larger number of related variables, including discharge. In some studies, such as this one, the measurement of turbidity has been used to accomplish this.

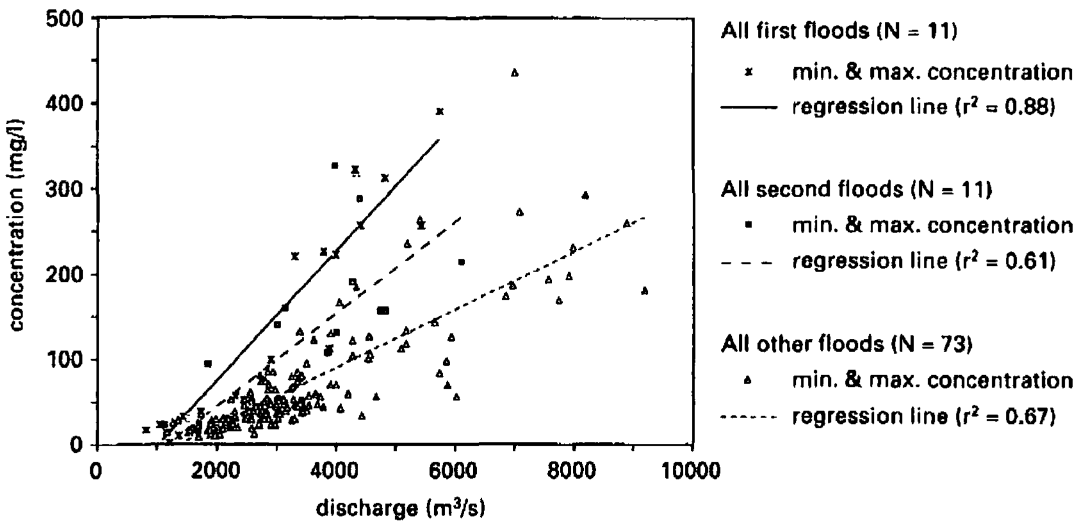

Figure 3.1. SSC-discharge relationships for the Rhine near Andernach between 1980 and 1990, separated into the first, second and subsequent floods in the hydrological year (from Asselman, 1999).

3.2.3. Turbidity measurements

Turbidity is defined as 'the reduction of transparency of a liquid caused by the presence of undissolved matter' (Lawler, 2005) and is often used as a proxy for suspended sediment measurements (e.g. Brasington and Richards, 2000; Nistor and Church, 2004). Turbidity has the advantage that it can be measured quasi-continuously using a turbidity probe with a data logger, so avoids the problems of water sampling by allowing sampling over the full range of discharges (Gippel, 1989; Foster *et al.,* 1992; Olive and Rieger, 1992; Walling *et al.,* 1992). However, the use of turbidity is not without its problems. The relationship between turbidity and SSC is not a constant one (Gippel, 1989). Turbidity is influenced by any form of solid in the water, which includes silt, clay, algae, plankton, and organic matter, and is also affected by bubbles and density discontinuities (Gippel, 1989; Lawler, 2005). Turbidity is a measurement of the light-scattering properties of suspended particles and consequently is affected differently by particles of different sizes, shapes and compositions (Gippel, 1989; Foster *et al.,* 1992; Gurnell *et al.,* 1992). Smaller particles have higher turbidity values than larger particles for the equivalent weight (Gilvear and Petts, 1985).

In order to use turbidity as a proxy for SSC, turbidity readings must be calibrated against known SSC values over a range of concentrations likely to be expected in the river. This may be done either using water samples from the river, or in a laboratory using sediment from the river being studied (e.g. Brasington and Richards, 2000; Nistor and Church, 2004). The relationship between SSC and turbidity may not be temporally or spatially constant in a given river, if the sediment sources differ between or within sediment transport events, or if concentrations of micro-organisms and organic matter vary seasonally (Gilvear and Petts, 1985). This is demonstrated in Figure 3.2. In these cases, a separate SSC-turbidity relationship must be calculated for each site (Gippel, 1995), or for seasonal sub-periods (Gurnell *et al.,* 1992).

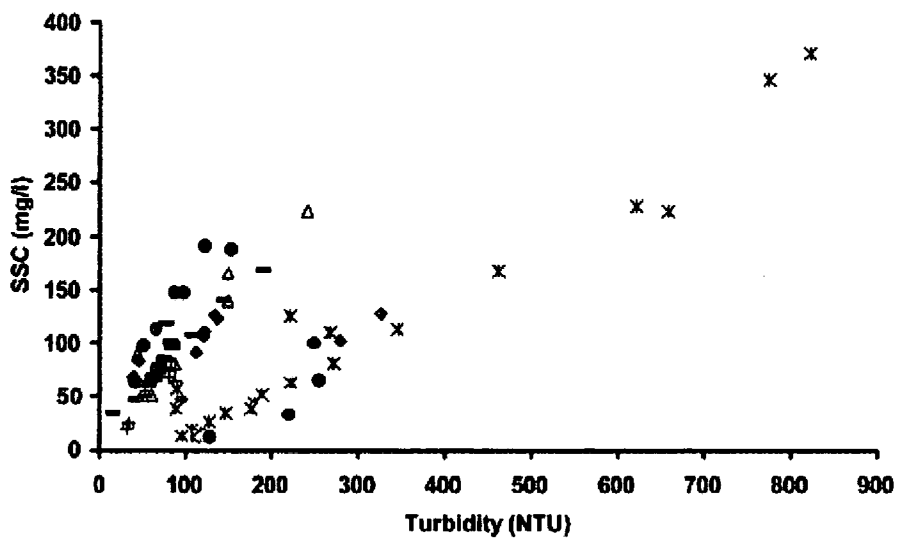

Figure 3.2. Between-storm variations in the relationship between turbidity and SSC in the River Swale, UK. Each symbol represents a separate storm (from Smith *et al.,* 2003).

Despite its limitations, turbidity remains a very useful tool for quantifying suspended sediment transport. Gippel (1995) argues that the loss of accuracy in SSC measurements by using turbidity as a proxy is more than compensated for by the benefit of the continuous measurements it produces.

3.2.4. Time integrated mass flux sampling

A limitation of water and turbidity sampling is the high operating cost, which means that it is often not feasible to operate sampling programmes at a high spatial resolution and over long time periods. Phillips *et al.,* (2000) described a cheap method for sampling suspended sediment using a time-integrated approach. The sampler consists of a length of pipe 1m in length and 100 mm in diameter, with inlet and outlet tubes of 4 mm diameter. The sampler is fixed in the channel, facing upstream. Water entering the sampler through the small inlet is slowed rapidly when it reaches the main chamber, which is of a much larger diameter. Sediment settles out in the tube, before water exits at the downstream end of the sampler. The sampler has been tested both in a laboratory and in the field by Phillips *et al.* (2000). In the laboratory the sampler retained between 31 and 71% of inflowing suspended sediment, although efficiency was greater at coarser grain sizes. Trapping efficiency is higher in the field due to the presence of flocs, which increase the effective particle size (Phillips *et al.,* 2000). Phillips *et al.,* (2000) advocate use of the sampler where large sediment samples are required for analysis of sediment properties, for sediment tracing for example; Russell *et al.* (2000) showed that the geochemical properties of sediment collected by the samplers were representative of the properties of the sampled population.

As well as collecting samples for geochemical analysis mass flux samplers can be used to sample time integrated relative sediment yields. However, the efficiency of mass flux samplers in representing suspended sediment yields is not thought to have been tested The only known study using time integrated mass flux samplers for the estimation of relative sediment flux in a catchment is a preliminary report on sediment flux in the Esk by Bracken and Warburton (2005). Systematic variations in yield between sub-catchments were found in these studies although the effects of sampler blockage and position in the channel on yields could not be quantified.

3.3. Project methods

Having taken into account the advantages and disadvantages of the various suspended sediment sampling methods discussed above, a suitable range of methods was developed in order to meet the project objectives.

3.3.1. River monitoring and storm sampling

At both main monitoring sites, Danby and Grosmont, stage, rainfall and turbidity were logged on a Campbell CR10X data logger, using 3 minute scan intervals and 15 minute log intervals. Logging was carried out from November 2005 until June 2006. Stage was measured using a Druck PDCR1830 pressure transducer and rainfall was recorded by a tipping bucket ARG100 gauge. A calibration problem with the pressure transducer at Grosmont resulted in stage data of a lower resolution than at Danby, but the magnitude and timing of events is correct. Turbidity was measured with an Analite 390 probe to give a quasi-continuous proxy record of SSC, following calibration against known SSC values. This should help avoid the problems due to infrequent sampling discussed in Section 3.2. Turbidity monitoring did not commence until March due to a firmware problem with the turbidity probes. Sigma 900 Max and Sigma 900 automatic water samplers were deployed at Danby and Grosmont respectively. They were programmed to take twelve water samples of 500 ml at 15 minute intervals and a further twelve at 30 minute intervals when triggered by a float switch at high flow. This stratified sampling strategy ensured sampling of a range of flow stages during an event and a high resolution record of SSC variation. The float switch was set at different heights during the monitoring period to enable sampling of different flood levels. A second Sigma 900 Max sampler with a float switch at a higher level was added at Danby in March to increase the sampling capacity. In the laboratory, following measurement of volume, the water samples were filtered using dried and pre-weighed Whatman glass fibre GF/C filter paper. The papers were then oven dried at 105 °C and reweighed to calculate the mass of the suspended sediment so the concentration could be calculated.

3.3.2. Spatial patterns of fine sediment mass flux

To add a greater spatial dimension to the study and allow more detailed examination of the areas of the catchment in which sediment transfer processes are most active, a network of 17 time-integrated mass flux sampling sites was set up in the main Esk and the major tributaries (Figure 3.3). The mass flux sediment samplers were based on the design described by Philips *et al.* (2000) and consisted of a 1 m length of polypipe tube of 0.1 m diameter, with a small inlet and outlet nozzle of 4 mm diameter at either end (Figure 3.4). The ends were streamlined, using funnels, to reduce flow resistance. The samplers were positioned in the direction of the flow and attached by plastic ties to two metal stakes driven into the river bed, so that the intake nozzle was about 0.1 m above the bed.

The mass flux samplers were emptied seven times at intervals of about three weeks, or as close to this as river conditions would allow (Table 3.1). This timescale allowed sufficient sediment to accumulate in the sampler for analysis, but was short enough that the accumulated sediment volume and characteristics could be closely related to specific storms and the hydro-meteorological conditions of each sampling period. In the laboratory the trapped water and sediment from each mass flux sampler was put into a tank for three days to allow the sediment to settle out. The water was then siphoned off and filtered (as described above) to calculate the mass of suspended sediment. The remaining sediment was dried and weighed. The mass of the dry sediment was added to the suspended sediment mass to calculate the total mass of trapped sediment.

Figure 3.3. Locations of mass flux samplers in the upper Esk catchment.

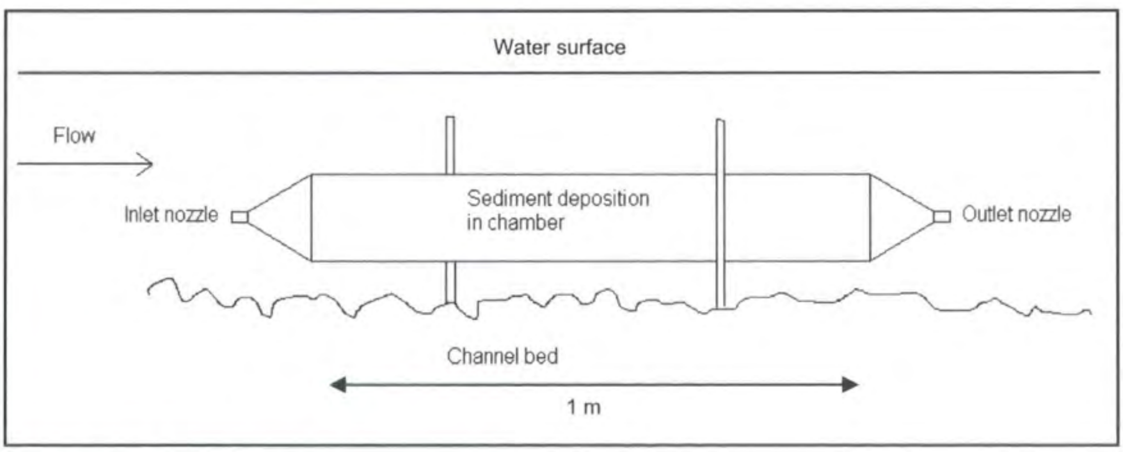

Figure 3.4. Mass flux sediment sampler.

The accuracy and precision of sediment yields from mass flux samplers deployed over the timescales used in this project have never been tested. At Danby two samplers were positioned about 10 m apart in the river. A comparison of the results from each will allow a preliminary assessment of the precision of the technique.

Table 3.1. Dates of mass flux sampling periods.

Sampling period	Dates
1	13th December 2005 – 12th January 2006
2	12th January – 1st February 2006
3	1st February – 23rd February 2006
4	23rd February – 21st March 2006
5	21st March – 20th April 2006
6	20th April -16th May 2006
7	16th May – 5th June 2006

3.3.3. Surveys of channel and riparian characteristics

Field survey was necessary in order to gain a fuller understanding of the catchment characteristics and to facilitate an analysis of suspended sediment dynamics. In February and March 2006 surveys of channel and riparian characteristics were carried out along the main Esk and all of the tributaries on which mass flux samplers had been deployed. A handheld Garmin e-trex GPS receiver was used to delineate a reach of channel where the processes occurring were relatively homogeneous. This was assessed for a range of parameters relating to erosion and fine sediment input susceptibility (Table 3.2). These were then compiled in a GIS database using ArcMap software.

3.4. Summary of approach

The flowchart below (Figure 3.5) summarises the methods the project has adopted. Sediment yields collected from mass flux samplers allow identification of the areas of the catchment in which suspended sediment supply and transport processes are active, while channel and riparian mapping allows yields to be related to channel characteristics. High resolution sampling of water during high flow events allows for detailed analysis of suspended sediment behaviour, and provides samples at a range of discharges to enable calibration of turbidity readings with SSC. Continuous monitoring of flow and turbidity enable the examination of the relationship between these variables in two parts of the catchment, at between and within storm scales. By relating the patterns observed in SSC to storm characteristics as determined from flow and rainfall records, dominant sediment transfer processes can be inferred. The final objective draws together the first three objectives, thus incorporating results from all the methodologies to understand the system as a whole.

Table 3.2. Parameters used to classify channel banks and stream sediment inputs.

Parameter	**Measurement**	**Classification**
Bank height	Height (m)	
Bankfull width	Width (m)	
Woody vegetation bank cover	Percentage	
Non-woody vegetation bank cover	Percentage	
Riparian land use	Class	Arable Pasture Woodland Moorland Other
Dominant bank material	Class	Fines Sand Gravel Artificial Obscured Other
Dominant type of erosion	Class	Subaerial - rain splash or freeze thaw Fluvial - entrainment of bank by river Geotechnical - internal collapse Burrowing Poaching Tree scour Footpath Soil piping
Extent of erosion	Class	1 - 4
Dominant bed material	Class	Sand Gravel Boulders
In-channel fine sediment storage	Number of sand or silt bars recorded per km	
Lateral connectivity	Number of non-channel point sediment inputs recorded per km	
Extent of livestock poaching	Number of occurrences of poaching recorded per km	

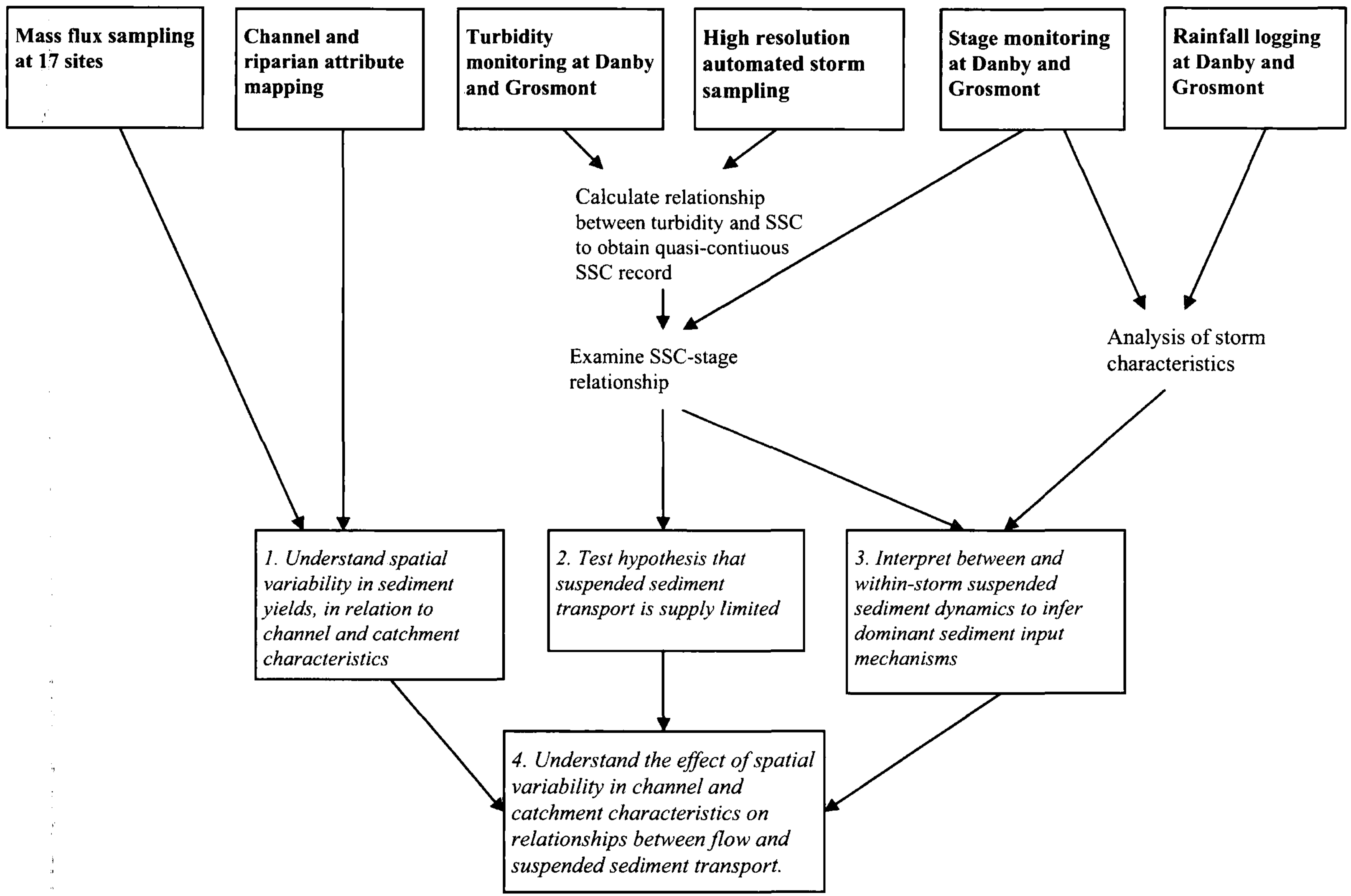

Figure 3.5. Relationship between methods (bold) and project aims (italic).

4. Spatial variability in sediment supply and transfer

4.1. Introduction

Knowledge of the spatial variability in the rate and nature of sediment supply is of key importance to the interpretation and understanding of the dynamics of fine sediment transfer in the River Esk. In this chapter sediment yields from the time integrated mass flux samplers will be analysed to show the dominant areas of sediment transfer. The mapped channel and catchment characteristics will be analysed in relation to the sediment yields to determine the dominant sediment sources and how these vary spatially. This will form the background for Chapter 5, where the spatial patterns in sediment supply rates and processes will provide a context for the analysis of temporal dynamics in suspended sediment transfer.

4.2. Time integrated mass flux suspended sediment yields

The yields from the mass flux samplers represent a measurement of the total load of suspended sediment passing through a small area of the river cross section (i.e. the sampler intake nozzle) over the period of sampling. The sediment mass, *M*, collected in a sampler during a time period, *t*, is given by the equation

$$M = n\int_0^t CV\delta t \qquad \text{(Equation 4.1)}$$

where *n* is the sampler nozzle diameter, which is constant, *C* is the SSC and *V* is the velocity of the flow entering the sampler nozzle. As the mass flux samplers collect sediment passing through one part of the river cross section, the yields collected do not represent loads. However, sediment loads and specific loads are useful measurements as they allow comparison of rates of sediment delivery between different channels and reaches. Using the mass flux yield, *M*, load, *L*, can be estimated from the equation

$$L = M \int_0^t \frac{A}{n} \delta t \qquad \text{(Equation 4.2)}$$

where A represents the cross sectional area of the flow. Stage was only recorded at Danby and Grosmont during the sampling periods, so a record of A at each mass flux sampling site is unavailable. Absolute loads could not, therefore, be calculated. Relative loads had to be calculated by multiplying the yield from each sampler by a weighting factor, which was based on a measure of the cross sectional area of the flow at each site.

4.2.1. Development of a mass flux weighting factor

Two different estimates of relative flows at each of the sites were compared. The first method was to measure the width and mean depth of the flow at each site on a given day, and multiply these to give the cross sectional area. The measurements were taken on a dry day during low flow when discharges were relatively constant throughout the day. This measurement provides an accurate estimate of the cross sectional area of the flow. However, the limitation of this method is that it assumes that the discharge and flow cross-sectional area changes at the same rate in each of the channels. This assumption is likely to be false because rainfall is often unevenly distributed across the catchment and flow may respond differently to rainfall in different channels. Although designed only to weight sites according to their relative cross section area, low flow measurements are not representative of the flows at which most sediment transport occurs.

The second method used was to estimate the bankfull flow capacity at each sampling site. This was determined by observing the channel bank morphology. The height of the dominant channel-forming flow was used to represent bankfull depth (Figure 4.1). The channel width was measured at this point and channel depth was measured at intervals across the channel. These measurements were multiplied to give a bankfull cross sectional area. However, bankfull discharge depths were difficult to define at some sites, especially where channel form was controlled by bedrock (e.g. Eller Beck), by artificial bank structures (e.g. Egton Bridge), by large numbers of trees (e.g. Glaisdale and Butter Becks), or by bank slumping (e.g. Duck Bridge). The method assumes that bankfull discharges occur with the same frequency at each site. This may not be the case as the flow regime in tributaries is likely to vary due to different responses to rainfall and because rainfall is unlikely to be evenly distributed across the catchment.

Figure 4.1. Example of bankfull cross section area estimation at Danby.

Weighted mass flux loads calculated using both methods assume that the SSC and velocity of the water passing through the sampler nozzle is representative of the entire cross section. This is likely to be a false assumption because it is acknowledged that flow velocity increases exponentially with distance from the channel bed. It has also been shown that in some rivers SSC is neither constant with depth nor width. Larger particles are likely to be carried nearer to the channel bed (e.g. Horowitz *et al.* 1989). Suspended sediment samples taken across a section of flow at Danby showed higher concentrations close to the channel banks (see Section 5.3.2). In order to minimise bias due to the effects of this variability the positioning of the samplers was consistent between sites. Samplers were positioned in the centre of the channel (where water depths would allow) and with the nozzle approximately 10 cm above the bed, although at some sites bed levels altered during sampling periods due to scour and deposition. This consistency between sites should mean that relative sediment loads are less affected by cross sectional variations in suspended sediment flux.

Comparison of the two methods showed some scatter in the relationship between the two values (Figure 4.2). Butter Beck, Glaisdale Beck and Six Arch Bridge have higher bankfull flow cross sectional areas, relative to their low flow cross sectional areas. Egton Bridge and Grosmont have lower bankfull flow cross sectional areas, relative to their low flow cross sectional areas. Some of this variability is due to measurement error and error due to difficulty in defining bankfull depths. Differences in the shapes of channels may also cause different relationships between low flow and high flow cross-sectional areas. The forms of the different channels may be adjusted to flows of differing magnitudes and frequencies, so the estimated bankfull discharge may represent a flow of a different relative magnitude in each channel.

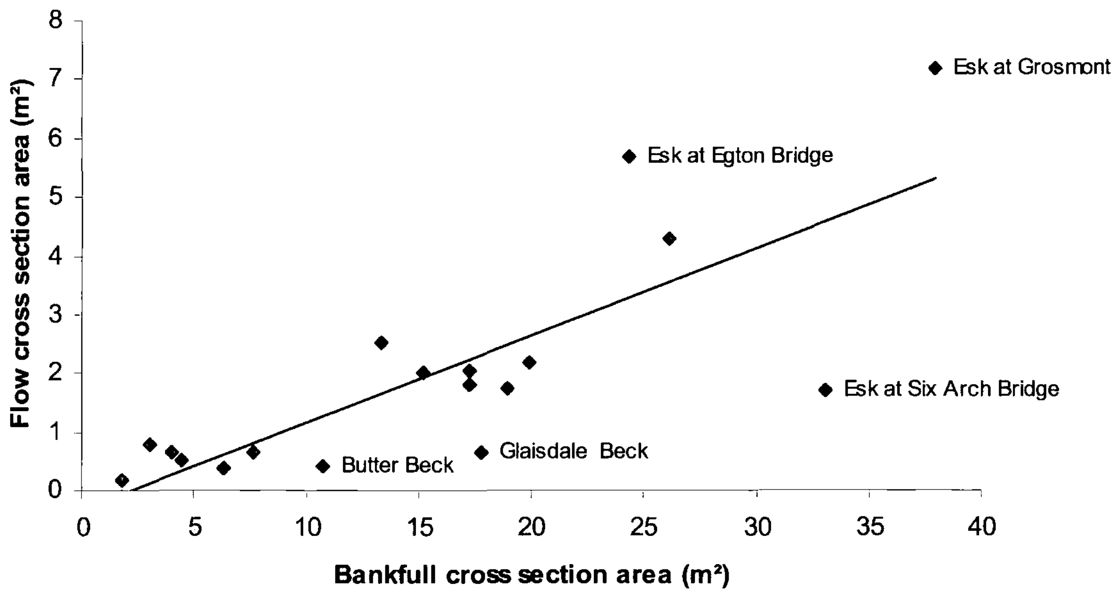

Figure 4.2. Comparison of cross-section area estimates at the mass flux sampling sites using two different methods ($R^2 = 0.63$).

Bankfull cross-sectional area was chosen as the measurement to be used for the mass flux yield weighting factor (Table 4.1). Typically, the flows which define the channel form are also the flows which transport the most sediment, so are likely to give a better estimate of relative loads from the mass flux samplers than measurements of low flow cross section area. Although the measurements of low flow cross sectional area are probably more precise, they are less representative of sediment-transporting discharges.

Although the bankfull cross section area weighting was derived independently of catchment area, a scatter plot of bankfull cross section area against catchment area shows a reasonably strong relationship ($R^2 = 0.67$), due to the morphometric relationship between these two variables (Figure 4.3). Scatter can be accounted for by possible variation in the specific discharge and flow regime in different sub-catchments and by differences between the adjustment of the channel form at each site to the flow, due to differences in substrate strength.

Table 4.1. Cross section area weighting factors for mass flux sampling sites.

Site	Cross section area weighting factor
Tower Beck	1.8
Butter Beck	10.7
Danby Beck	7.7
Great Fryup Beck	4.0
Glaisdale Beck	17.8
Baysdale Beck	3.0
Westerdale Beck	6.3
Commondale Beck	4.4
Eller Beck	15.2
West Beck	19.0
Esk at Six Arch Bridge	33.0
Esk at Danby	17.2
Esk at Duck Bridge	13.3
Esk at Lealholm	19.9
Esk at Glaisdale	26.1
Esk at Egton Bridge	24.3
Esk at Grosmont	38.0

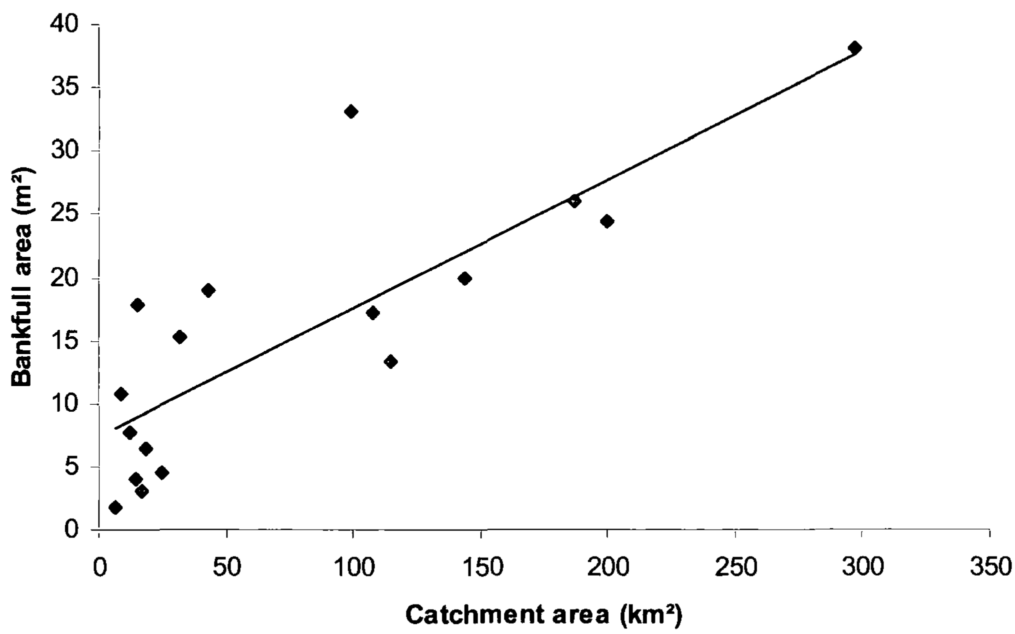

Figure 4.3. Relationship between bankfull cross sectional area and catchment area of mass flux sampling sites ($R^2 = 0.67$).

A plot showing only sites on the main Esk (Figure 4.4) shows a much better relationship because all the cross sections are from the same river, and therefore adjusted to the same flow regime. The Esk at Six Arch Bridge is an anomaly, with a much higher bankfull capacity compared to its catchment area. At this site bankfull depth was difficult to define because the channel is very incised and because it is immediately below a bridge, which has caused channel widening. The estimate of bankfull capacity is therefore likely to be too high. This discussion highlights the difficulty in measuring relative discharges in un-gauged catchments. In order to overcome this, a distributed hydrological model for the Esk catchment is needed. This would allow discharges to be computed at any channel cross section.

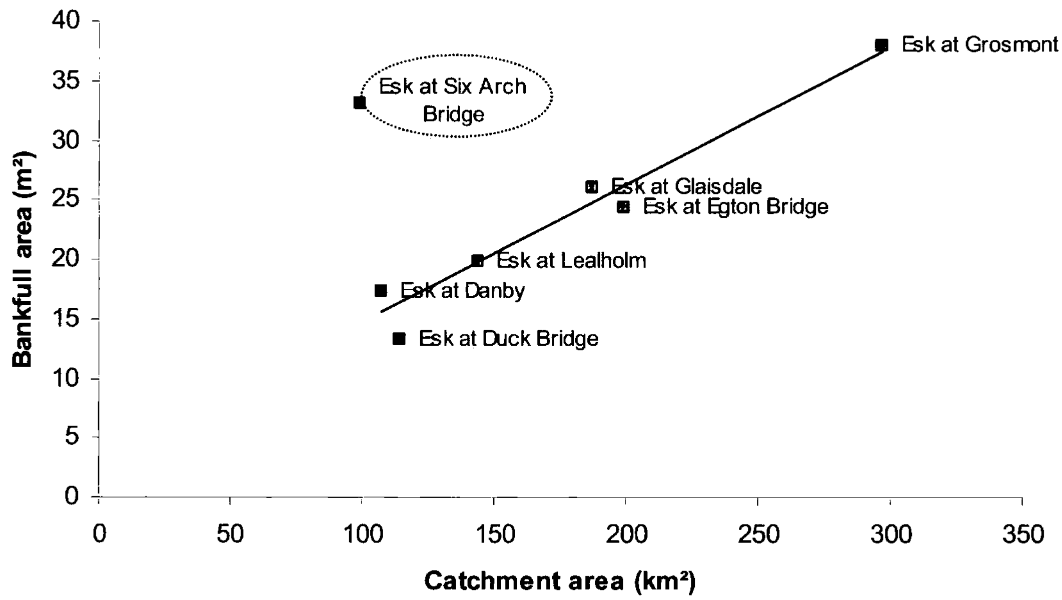

Figure 4.4. Relationship between bankfull cross sectional area and catchment area for mass flux sampling sites in the main Esk, omitting Six Arch Bridge ($R^2 = 0.95$).

4.2.2. Weighted mass flux loads and specific yields

The cross-section-area-weighting-factor for each of the mass flux sampling sites, A_{bf}, was multiplied by the yield from each sampler to give a relative load estimate, L_r:

$$L_r = MA_{bf} \quad \text{(Equation 4.3)}$$

An estimate of the relative specific sediment load, L_{sr}, at each sampling site was calculated from the equation

$$L_{sr} = MA_{bf}a^{-1}d^{-1} \quad \text{(Equation 4.4)}$$

where *a* represents catchment area and *d* is the length of the sampling period in days.

The relationship between mean weighted mass flux load and catchment area at each sampling site is shown in Figure 4.5. The expected pattern of increasing sediment load with increasing catchment area can clearly be seen. This relationship is strongly dependent on the positive relationship between channel cross section area and catchment area (Figure 4.3), as weighted loads are a function of the cross section area. Figure 4.6 shows that sites on the main Esk at Glaisdale, Egton Bridge and Grosmont have the highest weighted loads, as would be expected, due to the higher discharges and hence larger cross section areas at these sites. Tributaries generally have lower loads because of their lower discharges. However, Butter Beck has a high load, despite its small catchment area. Glaisdale Beck also has higher loads than other tributaries of similar catchment area.

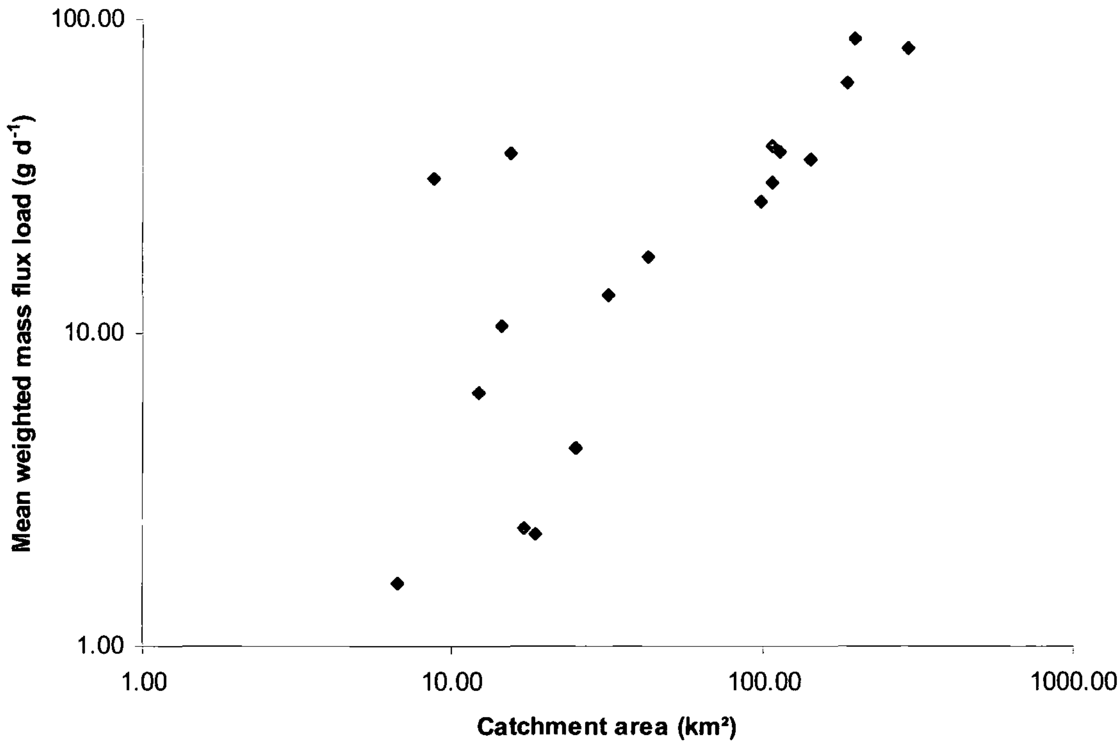

Figure 4.5. Relationship between mean weighted mass flux load and catchment area ($R^2 = 0.79$).

Examination of the spatial distribution of weighted mass flux loads shows a division within the catchment (Figure 4.7). In the catchment above Great Fryup Beck estimated weighted sediment loads in the main Esk are greater than total inputs from the tributaries. This implies that the main contribution of sediment to the river is from the main channel, from unmonitored sediment inputs into the main channel or from the reaches of tributaries downstream of the sampling locations. Downstream of Great Fryup Beck, weighted sediment yields from tributaries account for the total increase in sediment loads at sites along the main Esk. This indicates that the tributaries are the dominant sediment source in this part of the Esk. Processes contributing to suspended sediment supply and transfer are, therefore, not consistent throughout the catchment, but operate favourably in certain sub-catchments. This is likely to be related to differing channel and catchment characteristics.

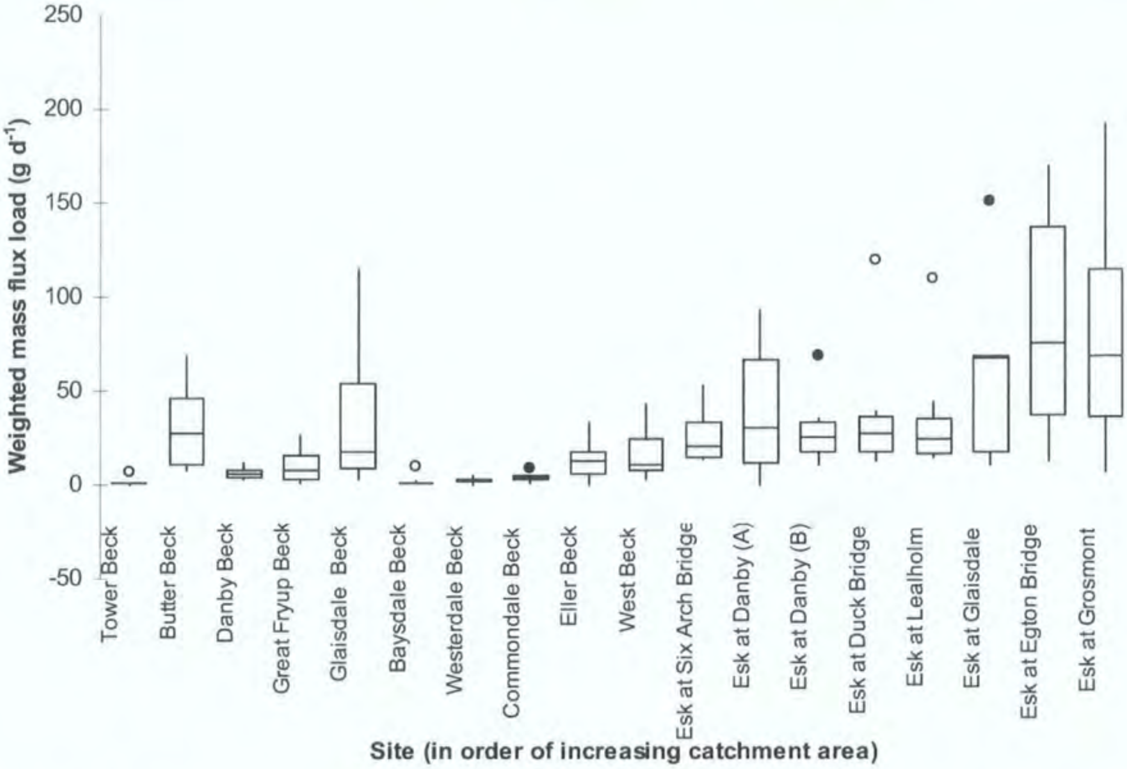

Figure 4.6. Box plot showing the median, quartiles and range of weighted mass flux loads at each sampling site.

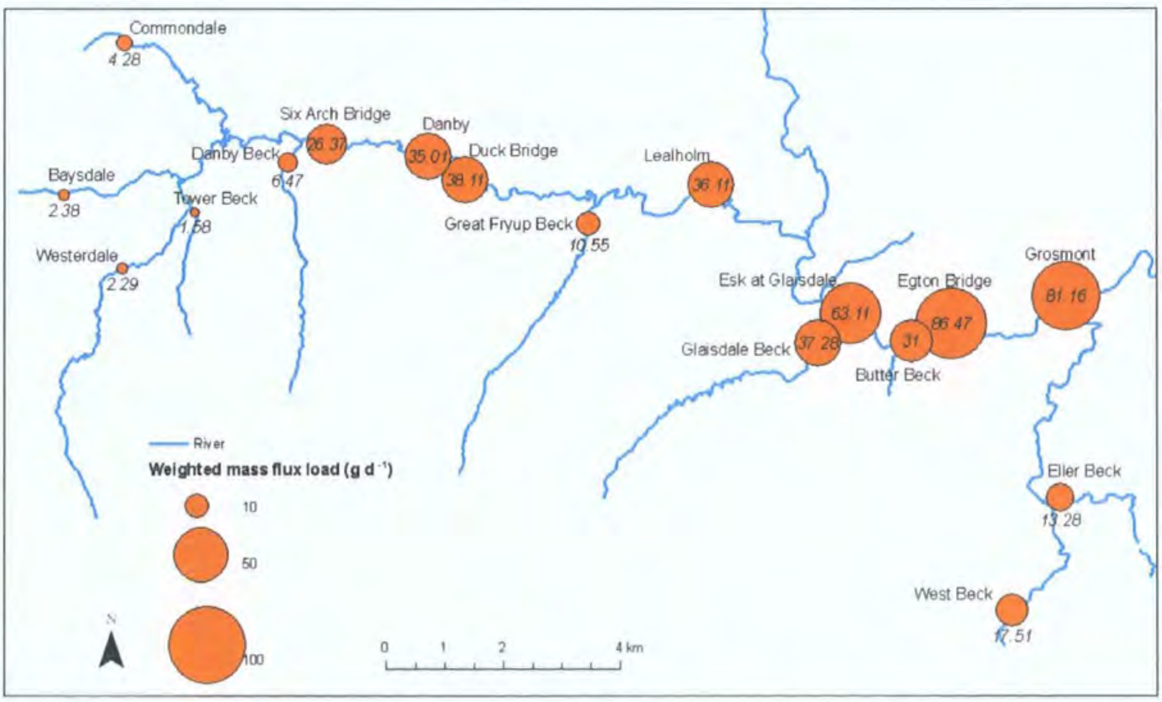

Figure 4.7. Spatial distribution of mean weighted mass flux suspended sediment loads, shown by proportional circles.

The specific weighted mass flux yield shows how much sediment is being produced per km², allowing the most important sources for sediment transfer to be determined.

Different relationships between specific sediment yield and catchment area are discussed in Section 2.2.1. The low intensity land use and the occurrence of Quaternary glacial sediments in the Esk catchment might make the Church and Slaymaker (1989) model most applicable to the Esk.

The specific weighted mass flux yield data for the Esk were plotted against catchment area to test whether either model holds for the Esk catchment (Figure 4.8). The poor relationship between specific weighted mass flux yield and catchment area ($R^2 = 0.09$) shows that the efficiency of sediment production and transfer processes is not simply related to catchment area. Figure 4.8 shows that two sub-catchments have significantly higher specific weighted sediment yields than all others. These are Glaisdale and Butter Becks. Both the highest and lowest specific sediment yields can be found in small catchments, while at larger catchment areas the specific sediment yield is more consistent and falls between the two extremes.

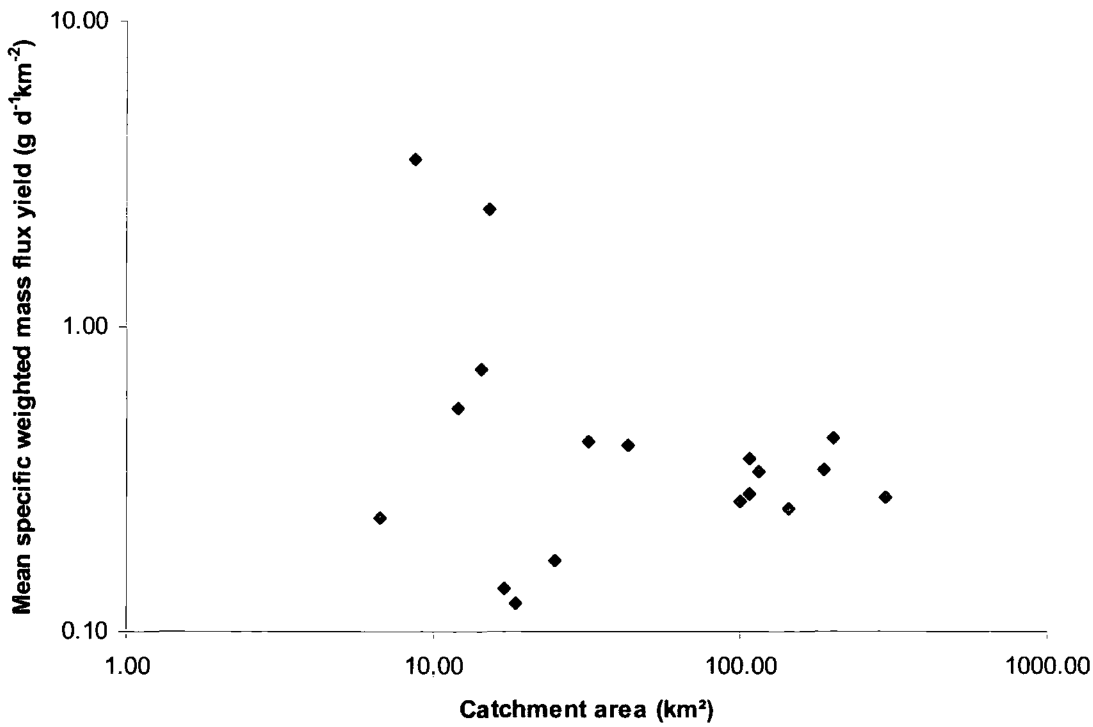

Figure 4.8. Relationship between mean weighted specific mass flux sediment yield and catchment area ($R^2 = 0.09$).

The spatial trends in specific weighted mass flux yield for each sub-catchment are shown in Figure 4.9. Butter and Glaisdale Becks supply sediment at rates an order of magnitude greater than most other sub-catchments. Great Fryup Beck and Danby Beck have the third and fourth highest specific yields. These tributaries conform to the model of small catchment areas having higher specific sediment yields and are those with catchments further to the east. In contrast, four tributaries, Tower Beck, Baysdale Beck, Commondale Beck and Westerdale Beck, have the lowest specific sediment yields of any sampling site. These are all headwater catchments. This variability in specific sediment yields between the tributaries shows that sediment production and transfer processes do not operate consistently between sub-catchments and that certain parts of the Esk catchment are more important sources of fine sediment than others.

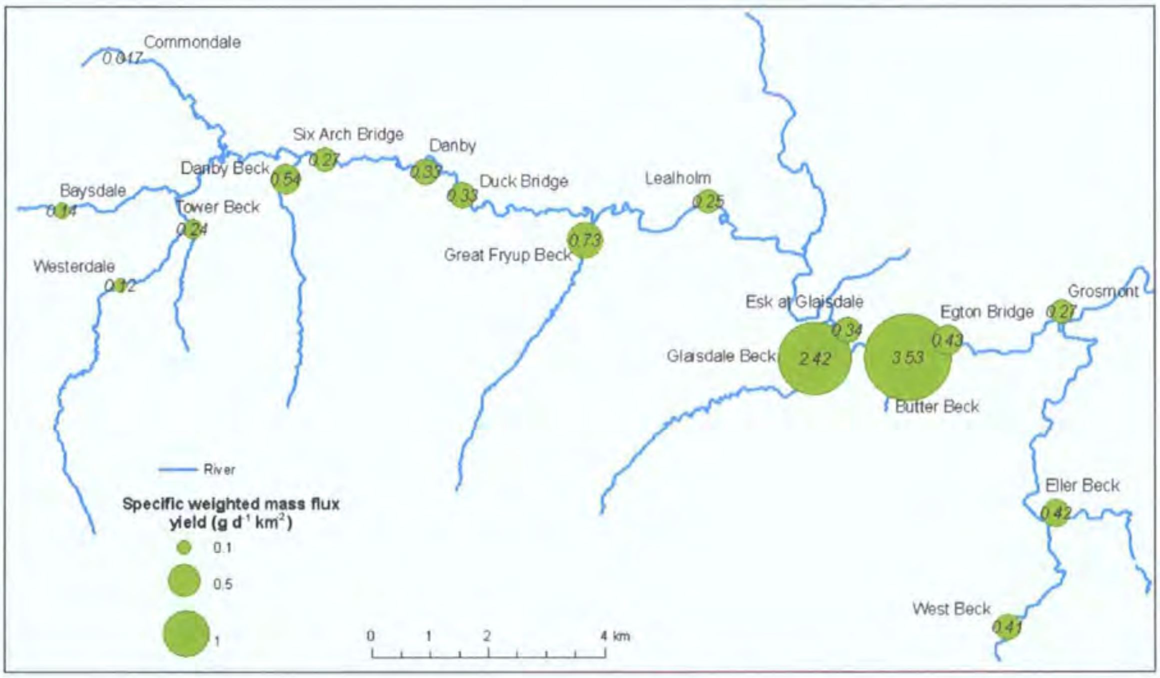

Figure 4.9. Spatial distribution of mean specific weighted mass flux suspended sediment yields.

4.3. Channel and catchment characteristics

The GIS database of characteristics of the main Esk and major tributaries, along with field evidence, will be used to analyse the morphology of the different parts of the Esk catchment in relation to the spatial variation in sediment loads shown above. The section has been split into the analysis of geology, channel characteristics and riparian characteristics, and the potential of these for the production and transfer of channel and non-channel sediment sources.

4.3.1. Geology

The surficial geology has a major influence on the catchment morphology. It dictates the substrates into which channels are formed and is therefore an important factor determining channel characteristics and suspended sediment production and transport. Figures 1.4 and 1.5 show the solid and drift geologies into which the Esk and its tributaries have eroded. The meanders of the Esk above Glaisdale are incised into a sandy floodplain, and the deposits from the glacial lake which once occupied the valley (Jones, 1999). The lower reaches of the Esk, between Glaisdale and Grosmont are eroded through more resistant glacial drift and bedrock and form steep sided valleys and gorges. The low yielding headwater tributaries identified in Section 4.2.2 are mainly eroded into consolidated sandstones and mudstones. The tributaries identified as having higher sediment yields are formed on boulder clay drift. Butter and Glaisdale Becks, the tributaries with the highest yields are both formed entirely on this substrate. Glacial drift is unconsolidated and therefore likely to be more easily reworked than consolidated material. This may be a factor causing higher sediment yields in the tributaries further east. In addition to this direct influence on suspended sediment yields, the underlying geology affects many of the channel and catchment characteristics which will be analysed in the following sections and therefore also has an indirect influence on suspended sediment yields.

4.3.2. Channel characteristics

Figure 4.10 shows that channel banks are highest on the main Esk upstream of Glaisdale, where mean bank height is consistently above 2 m and often above 3 m. The main Esk downstream of Glaisdale and the tributaries have mean bank heights of less than 2 m, with the exception of some high channel banks on the Murk Esk. Comparison of Figure 4.10 with Figure 4.11 shows that on the main Esk the highest banks correspond to reaches where bank material is sand, while boulders are the predominant bank material where banks are low. The two distinct morphologies on the main Esk reflect the operation of different channel forming processes and relate to the underlying substrate (Figures 1.4 and 1.5). Field observations indicate that the high channel banks in sandy material are not stable and are subject to a cycle of basal removal and slumping (Figure 4.12). The lower part of the Esk is strongly boulder and bedrock controlled, which limits scope for channel incision and instability (Figure 4.13). Channel bank material varies between tributaries and does not seem to be as closely related to channel bank height as in the main Esk. This is because the lower contemporary discharges of tributaries do not have the capacity to incise into bank material to the same extent as the main Esk. In Baysdale and Westerdale where meanders hit the edge of the floodplain, one channel bank may be a very steep slope, or bedrock outcrop. The high banks on parts of the Murk Esk correspond to outcropping sandstone and shale cliffs which occur in this strongly bedrock controlled tributary (Figure 4.14).

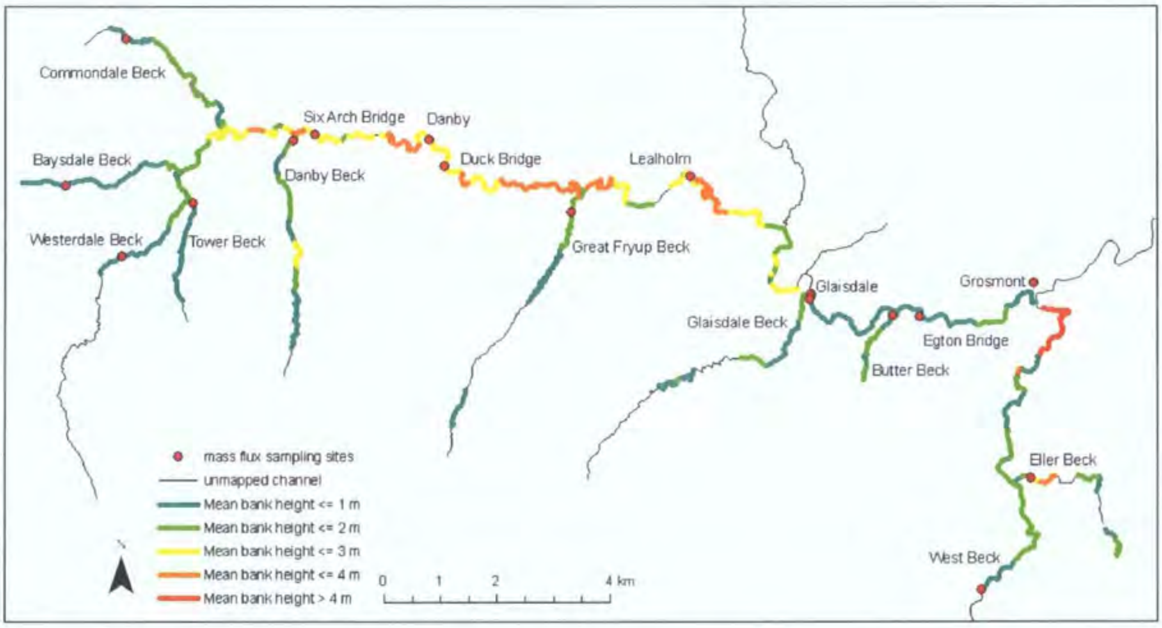

Figure 4.10. Bank height of River Esk channel and major tributaries.

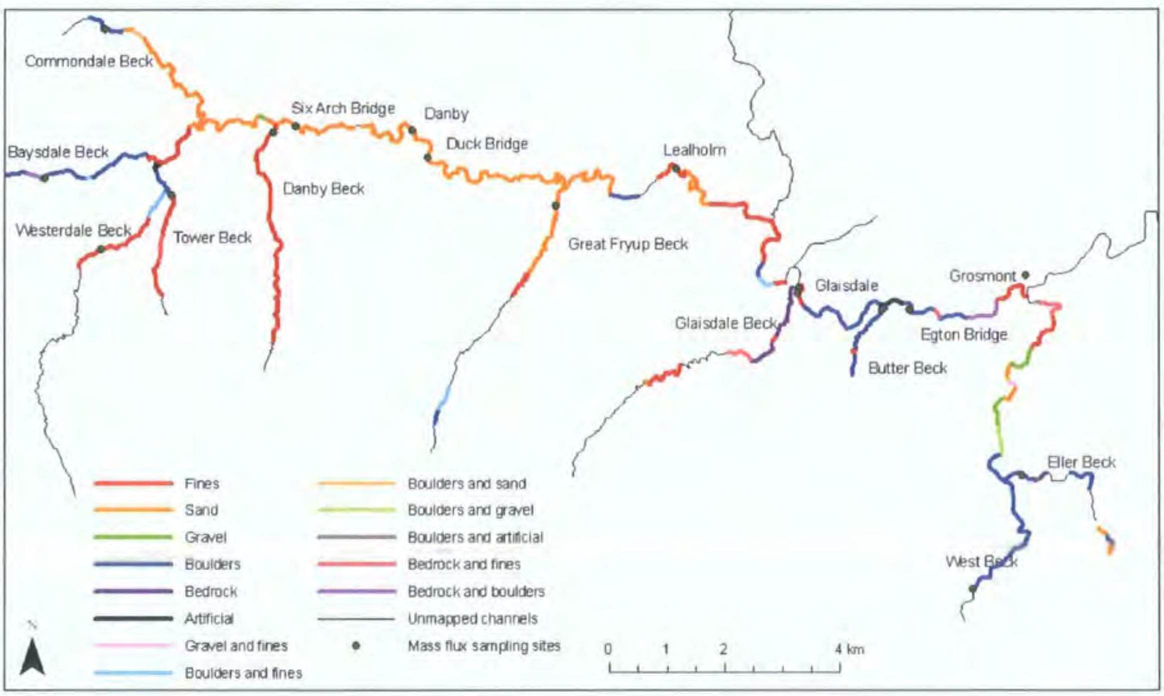

Figure 4.11. Bank material of River Esk channel and major tributaries.

Figure 4.12. Sandy slumping banks near Six Arch Bridge, typical of the upper part of the main Esk.

Figure 4.13. The main Esk channel below Glaisdale, showing rapid flow with boulders on bed and banks.

Figure 4.14. Bedrock cliff on the Murk Esk above Grosmont.

The dominant channel bank erosion type (Figure 4.15) corresponds with the bank material and height. Geotechnical failure is predominant where banks are high and sandy because sand is a non-cohesive material and is susceptible to failure where it forms a steep, high bank. Rotational slumping was more common type of failure, except where falling trees caused toppling of banks into the river. More geotechnical bank failures were observed on the outside of meanders, due to fluvial undercutting. Fluvial erosion is the dominant bank erosion type for most reaches where banks are formed of fines or boulders, which includes the main Esk below Glaisdale and all the tributaries except Commondale. The banks of many of the tributaries are lower in height so less susceptible to mass failure; fines are cohesive, which increases bank stability (Figure 4.16). Where boulders are present these are often surrounded by a matrix of fines which can be winnowed away during high flow events. However, the remaining boulders generally form a bank at a stable angle, which is resistant against all but the highest flows, because of the large clast size (Figure 4.13). This occurs in particular in the lower part of Glaisdale Beck, the lower main Esk and much of the Murk Esk. Subaerial erosion processes are dominant in reaches which have outcropping bedrock (Figure 4.14) as flow would never reach most of this material and the material is resistant to undercutting. Although trees were present on many of the channel banks, tree scour was only the predominant form of erosion on a section of the Murk Esk and upper Glaisdale Beck.

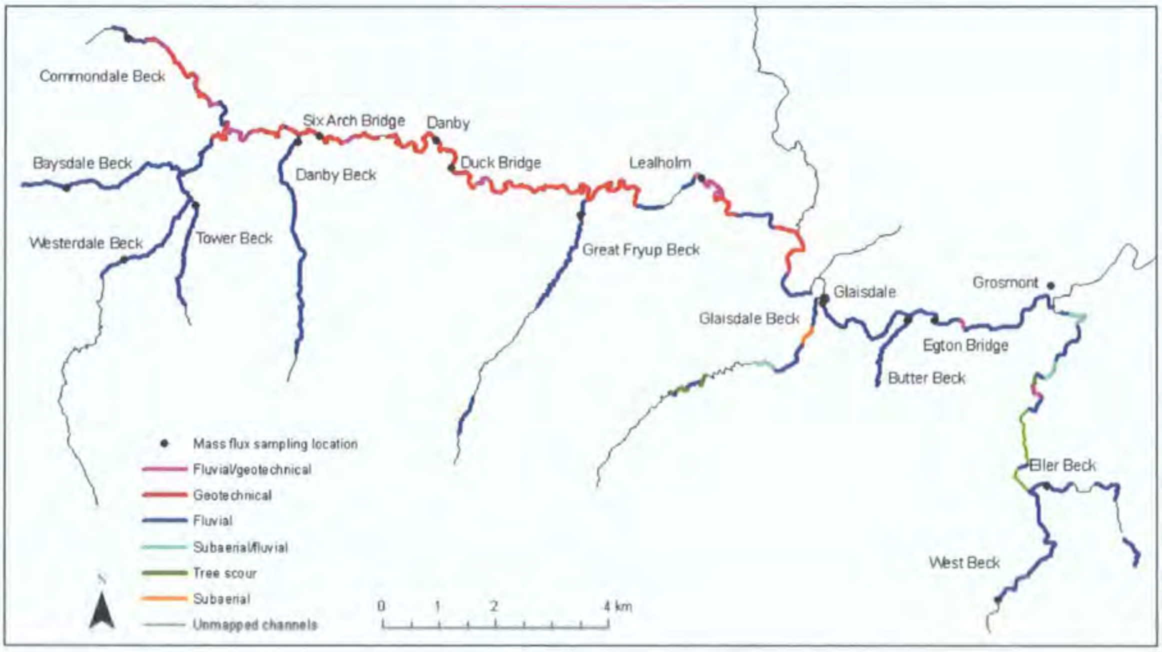

Figure 4.15. Erosion type of River Esk and major tributaries.

Figure 4.16. Undercutting of cohesive channel banks on Danby Beck.

The extent of bank erosion (Figure 4.17) can also be related to the bank height, material and erosion type. The areas of most extensive erosion are found in the upper part of the main Esk and correspond to high, sandy, slumping banks. This can help explain the greater importance of sediment supply from the main Esk channel in the upper part of the catchment. Erosion is less extensive in reaches where banks are mainly composed of boulders or fines. These reaches are generally found on the main Esk below Glaisdale, on the Murk Esk and in Baysdale Beck and correspond to areas where sediment supply is lower. Erosion extent is high in several tributaries. In Commondale and Great Fryup Becks this can be attributed to the non-cohesive, sandy banks. In Danby and Westerdale Becks extensive erosion of fines and of banks incorporating boulders and fines appears to be occurring. This is possibly because the mixed banks in these tributaries consist of matrix supported boulders, which are likely to collapse following winnowing of fines from the matrix. In the lower parts of the main Esk banks are more commonly formed of interlocking boulders, so are more stable.

It is important to recognise that the amount of fine sediment supplied from an eroding bank is dependent on the bank height as well as the erosion extent and dominant grain size. Extensive bank erosion on the upper main Esk is more significant in terms of sediment supply than extensive bank erosion in tributaries where banks are lower and hence the volume being eroded is smaller. This helps to explain why sediment yields and loads in Westerdale and Tower Becks are low, despite bank erosion extent being high.

Figure 4.17. Bank erosion extent of River Esk and major tributaries.

Channel bank vegetation cover is variable and related to erosion extent. In most of the Esk channel bank vegetation cover is between 50 and 90 percent (Figure 4.18). Lower vegetation cover is found on the main Esk upstream of Great Fryup Beck and is linked to the extensive slumping in these reaches. Lack of vegetation cover is likely to exacerbate slumping by reducing the number of plant roots stabilising banks and by exposing bank material to flow and subaerial erosion processes. Increased slumping, in turn, is likely to prevent bank vegetation becoming established, resulting in a positive feedback effect. Woody bank vegetation is very common along much of the Esk and its tributaries, though the density of trees varies. Trees may increase bank stability due to root cohesion. In sub-reaches of some of the tributaries the channel plan form was determined by the presence of trees, which would form the points of river bends. However, the trees only stabilised the bank locally and did not prevent erosion of other parts of the bank (Figures 4.19 and 4.20). In fact they may exacerbate erosion of other parts of the bank, by causing undercutting at the outside of a bend formed by a tree, or by causing scour on either side of the tree. Tree scour is only a dominant form of bank erosion in parts of Glaisdale Beck and the Murk Esk (Figure 4.15), although it did occur in combination with other types of erosion in other reaches. Trees directly contributed to bank retreat in many reaches due to the weight of the tree rending the bank more unstable. In reaches bordered by steep, wooded slopes, falling trees were commonly observed on the valley sides and probably contributed to mass wasting.

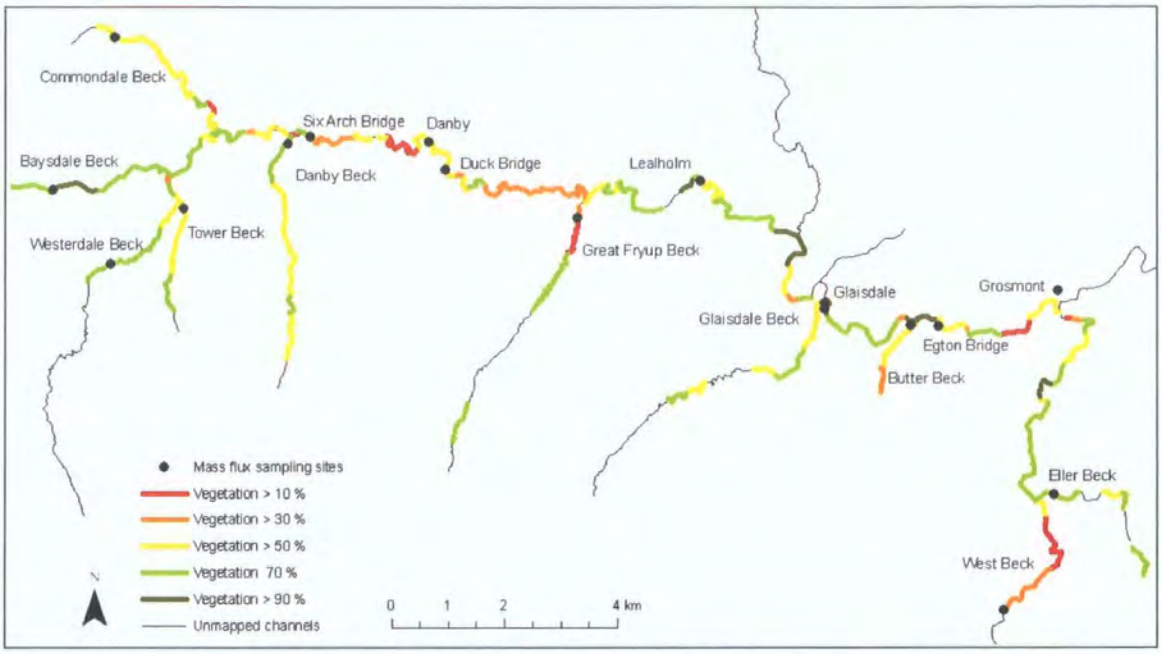

Figure 4.18. Total bank vegetation cover of River Esk and major tributaries.

Figure 4.19. Tree roots preventing bank failure on main Esk near Glaisdale.

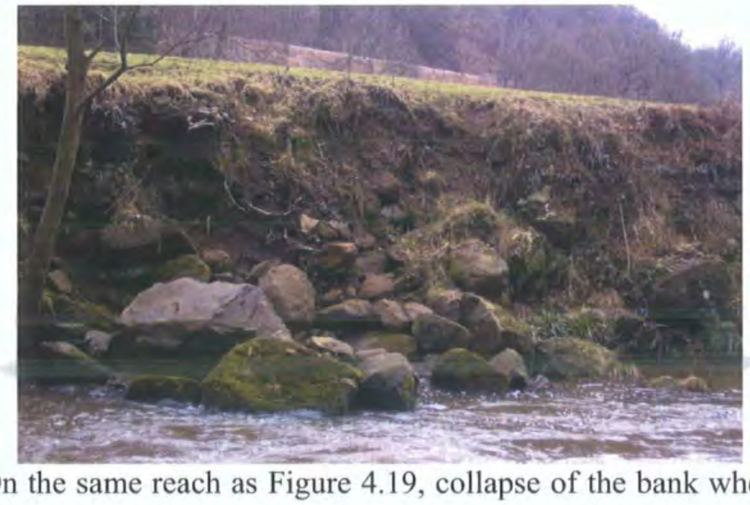

Figure 4.20. On the same reach as Figure 4.19, collapse of the bank where no trees are present.

The other role of trees is to cause blockage or damming of the river. This occurs more frequently in tributaries than the main Esk, because the lower depth and channel width make blockage easier. Trees and debris falling from banks or valley sides cause full or partial blockage of the channel. Sections of fallen bank, often brought about by tree-fall, also partially blocked some channels. Most debris blockages were not large enough to result in a pool forming, but nevertheless caused deposition of fine sediment behind, which is likely to be mobilised during high flow. In some instances trees completely dammed the river, behind which fine sediment was deposited in a pool (Figure 4.21), interrupting the downstream transfer of fine sediment. Overtopping or breaching of dams during high flow allows release of fine sediment stored behind log dams, which would result in an episodic pattern to fine sediment transport.

Figure 4.21. Debris jam in Tower Beck, typical of tree-lined tributary reaches.

Sediment input from channel banks may be enhanced by livestock poaching. This was observed very infrequently on the main Esk (Figure 4.22), but where it occurred it resulted in a large extent of bare sediment adjacent to the channel (Figure 4.23). A hotspot was found on the main Esk near Six Arch Bridge. In general the main Esk is well fenced to prevent livestock poaching, and the high, steep banks naturally prevent livestock access to the channel. Poaching was observed on all tributaries except Butter Beck, but still relatively infrequently, the highest concentration being found on a small area of upper Great Fryup Beck. Even infrequent poaching can, however, result in a significant expanse of exposed sediment on the channel banks which will provide an abundant sediment source to high flow events. Trampling by livestock on the banks of small tributaries flowing through pasture was seen at a number of sites and probably increases the load of sediment contributed to the main channels by these inputs.

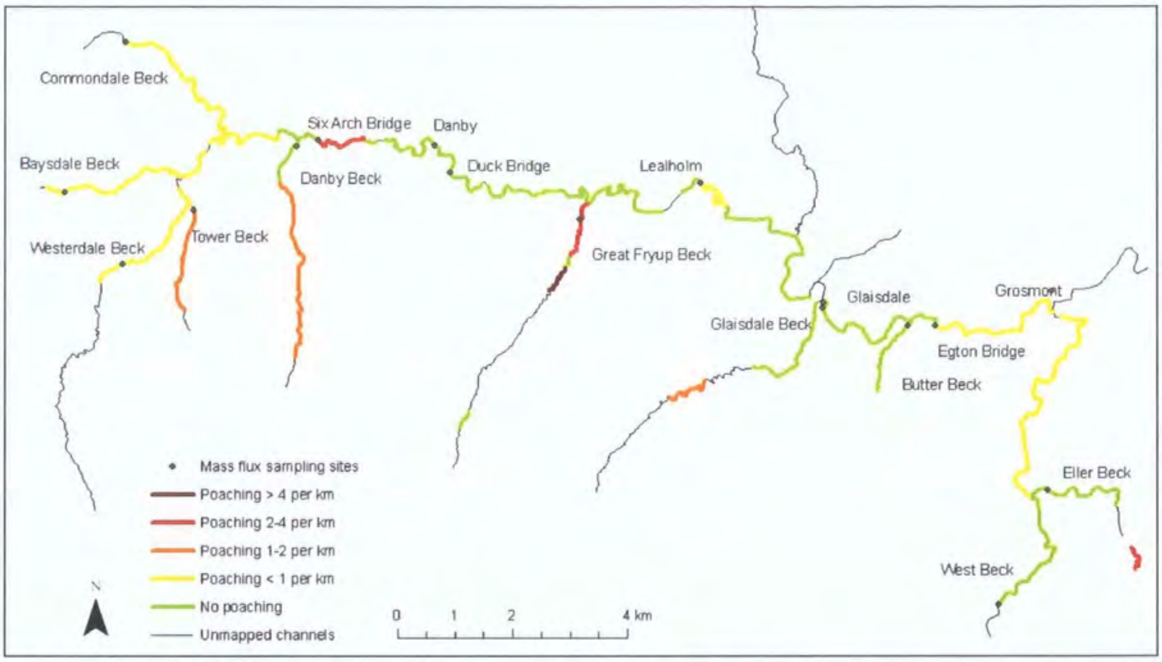

Figure 4.22. Evidence of livestock poaching on River Esk and major tributaries.

Figure 4.23. Livestock poaching on the main Esk near Six Arch Bridge.

Conversely, sediment production from channel banks may be reduced by artificial bank protection measures. These were found in several tributaries of the Esk and had generally been put in place by farmers. Figure 4.24 shows a typical style of bank protection, comprising brush wood woven between willow stakes. According to a farmer in Commondale, this type of bank protection had stabilised a bank which had undergone a serious collapse during a flood. Sediment is trapped and accumulates behind the willow stakes, increasing bank stability. Other bank protection measures include stone walls, which are common in the upstream parts of Danby Beck (Figure

4.25). The occurrence of increased sediment supply from poaching and decreased sediment supply due to bank protection is dependent on the farming practices in the reach in question. This is spatially variable due to the large number of landowners within even a single sub-catchment of the Esk.

Figure 4.24. Local channel bank protection in Commondale, using willow stakes and brush wood.

Figure 4.25. Bank protection in Danby Beck using stone walls.

Sediment stored within the channel can be mobilised during high flow events. Figure 4.26 shows the density of sand bars in the channel. Storage is high in the upper part of the main Esk. Channel gradient is low on the meandering floodplain section of the Esk above Lealholm (Figure 4.27) and the sediment supply from the channel banks in this section is sand, which is unlikely to be transported long distances because of the greater shear stress required, but is stored on the channel bed and as side and point bars. Sediment from slumped banks may also be stored within the channel before being mobilised by a high flow event. The high volumes of within-channel sediment storage above Lealholm are a further reason for the importance of sediment supply from the main Esk channel, relative to tributaries. The main Esk between Lealholm and Butter Beck has a low storage density, compared to the upper main Esk. In these downstream reaches the fine sediment supplied by the banks is clay and silt and the bedrock-controlled section near Glaisdale has a steeper channel slope (Figure 4.27). The smaller grain size and the higher capacity for transport probably cause most of the sediment produced in these reaches to be flushed straight through the system during high flow events, resulting in little within-channel storage.

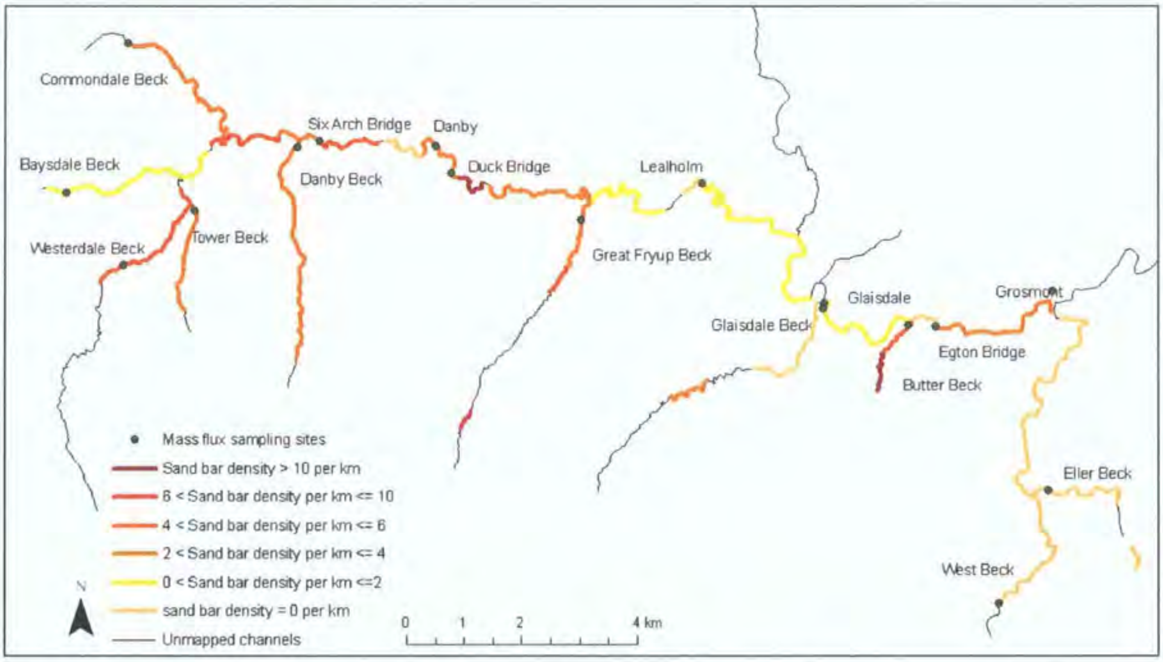

Figure 4.26. Sand bar density in River Esk and major tributaries.

The Murk Esk and lower Glaisdale Beck have no fine sediment storage in bars, reflecting their boulder and bedrock banks and steep channel gradients, which cause the rapid removal of any fine sediment. Storage in other tributaries, apart from Butter Beck, is moderate and commonly as lateral and point bars. The influence of debris blockages on in-channel sediment storage has already been discussed. In many of the sinuous tributaries pool and riffle sequences are a common bed form and are significant in determining the distribution of fine sediment storage in the channel. Fine sediment accumulates in the pools, between riffles consisting of coarser sediment. Fine sediment was also observed in some channels as a thin drape over bed gravels, in the spaces between bed gravels or within bars formed predominantly of gravel.

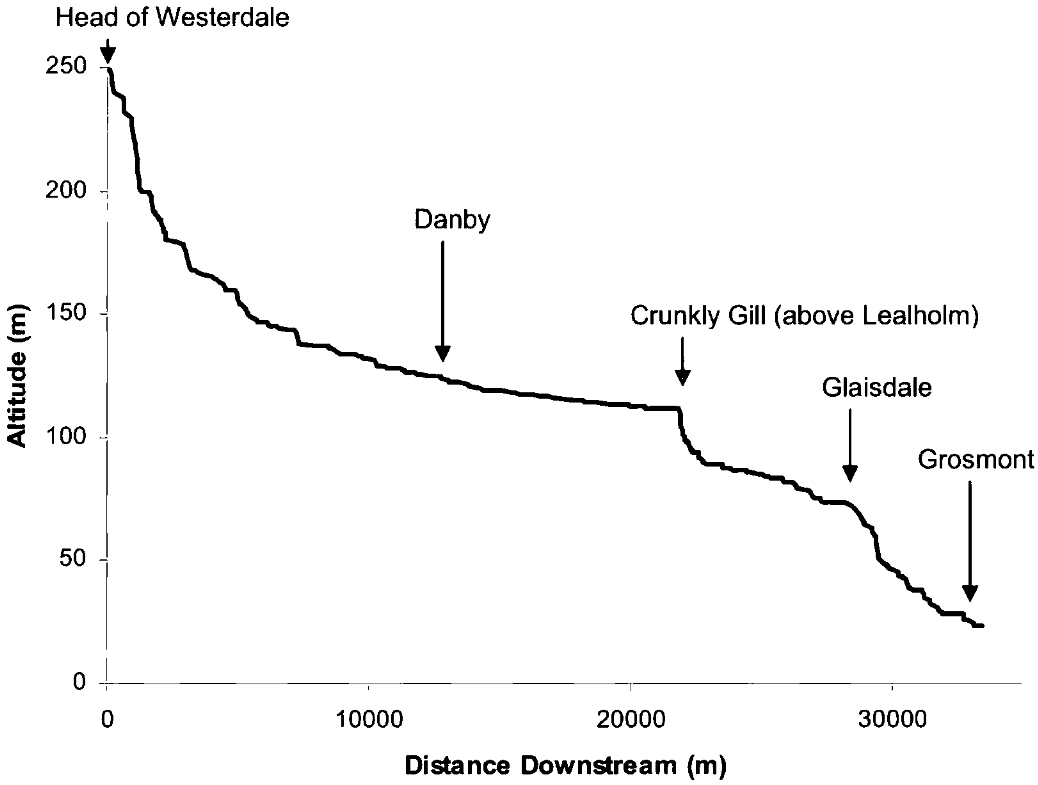

Figure 4.27. Long profile of the Esk channel from Westerdale to Grosmont.

Butter Beck has a high density of sediment storage which, when mobilised, is likely to contribute to its high sediment yields (Figure 4.27). However, when mapping this tributary an initial source for the stored sediment was not apparent. Its catchment is not intensively farmed and bank erosion does not appear to be a significant sediment input. However, consultation with representatives from the management authorities (Environment Agency and North York Moors National Park Authority) revealed the cause of the high sediment yields in Butter Beck. The beck had become overgrown and had accumulated large numbers of woody debris jams. These were cleared in 2001 as part of the River Esk Regeneration Programme, in an attempt to allow sea trout to return to the river to spawn. Although the trout did return to Butter Beck, the clearance had the added effect of releasing large amounts of stored sediment which had accumulated behind debris jams. This now provides an abundant source of within channel sediment which is available for transport during high flow events. The continuing importance of this sediment after five years demonstrates the high potential for sediment storage within tributary channels, particularly where large amounts of woody debris are present.

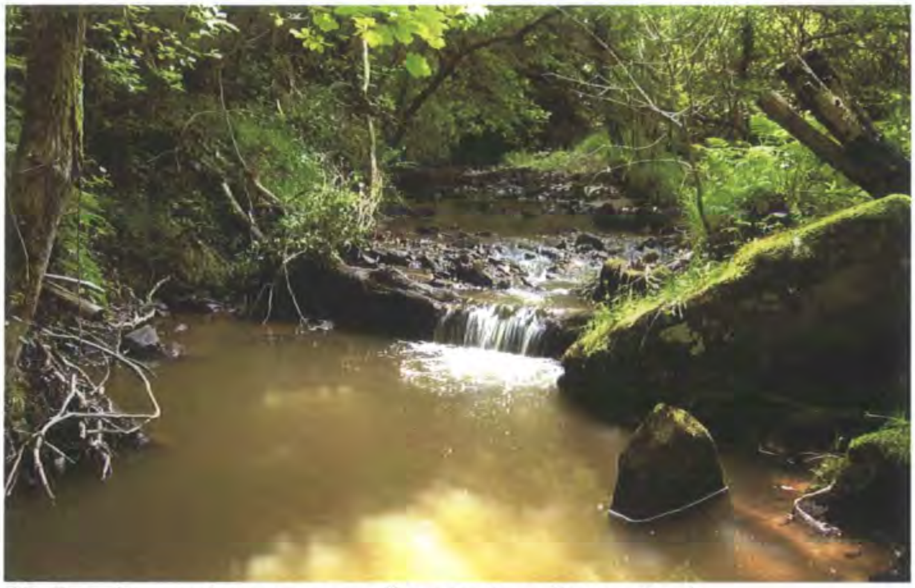

Figure 4.28. Log jam and upstream sediment store, Butter Beck.

4.3.3. Catchment sediment inputs

The importance of catchment sediment inputs is likely to be variable throughout the Esk because of the changing levels of connectivity between catchment sediment sources and the channel. The morphology of the Esk catchment does not conform to the conventional model of a downstream increase in floodplain width, due to its glacial legacy (Figure 4.29). The upper part of the main Esk has an extensive floodplain, while the lower part is more strongly bedrock controlled, with a small or non-existent floodplain and steep valley sides. Floodplains are present in some tributary catchments, but many also have sections of bedrock outcrop and steep valley sides. Floodplains act as buffers, preventing the transfer of sediment between hillslopes and the channel. Catchment sediment sources are therefore likely to be of lower importance in reaches with floodplains. Where valley sides are steep sources have a greater potential energy with which to reach the channel, so connectivity is likely to be higher. Steep valley sides are generally wooded (Figure 4.30) and relatively stable, except where falling trees result in possible elevated sediment supply to the channel. Some valley sides, such as in the lower Murk Esk and parts of the Esk between Egton Bridge and Grosmont, include areas of exposed bedrock, where subaerially weathered sediment is directly transferred into the river (Figure 4.14).

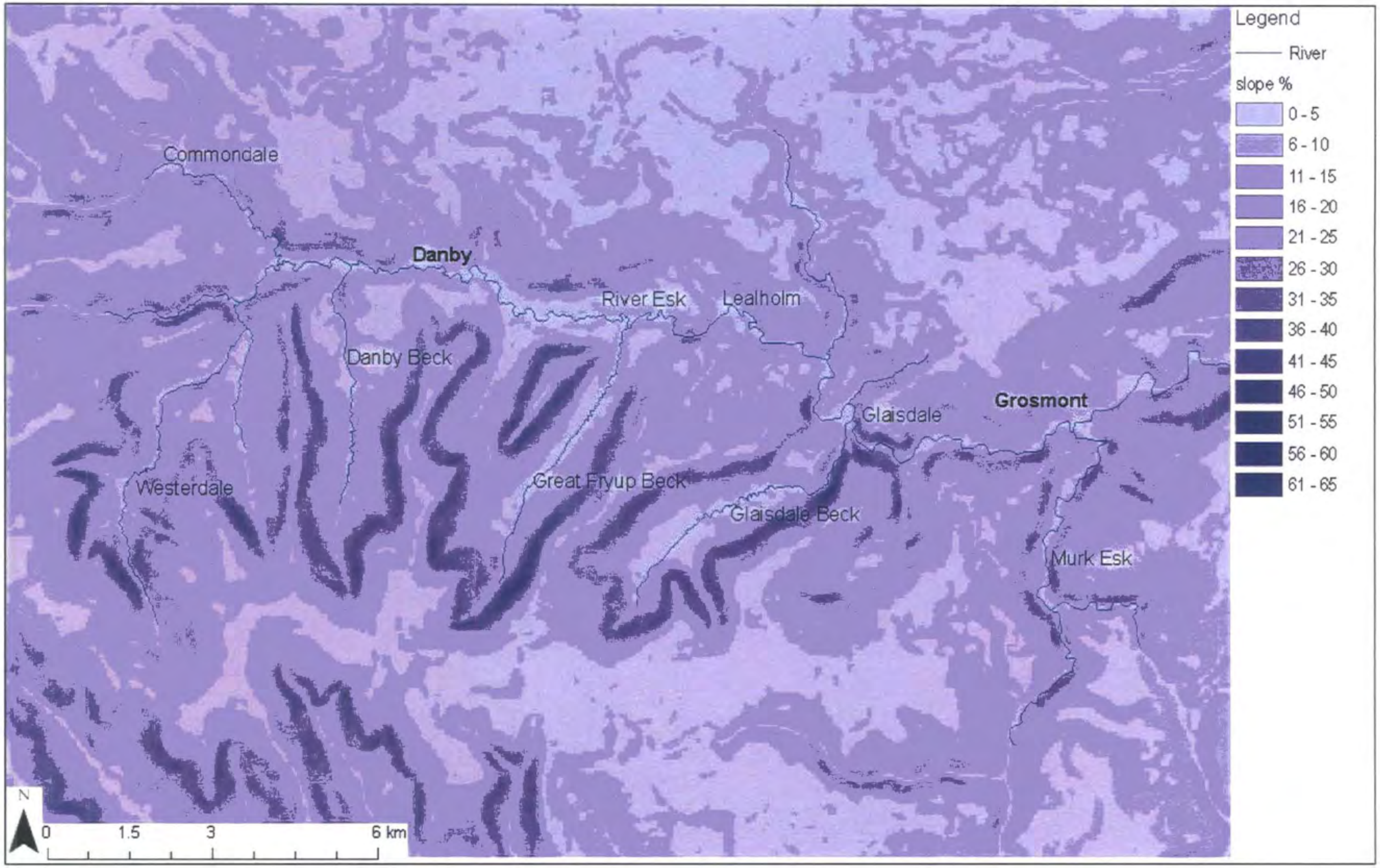

Figure 4.29. Slope gradients in the Esk catchment (data from Edina Digimap).

Figure 4.30. Steep, wooded banks below Egton Bridge.

The number of inputs of minor flow from the catchment to the channel is a good indicator of the lateral connectivity between the channel and any sediment sources in the catchment. These may be minor tributaries, surface runoff, pipe flow, ditches or drains. Figure 4.31 shows the density of these lateral flow inputs which were observed during field mapping of the Esk catchment. It would be expected that flow inputs are highest where channel banks are steeper and the floodplain is small. According to Figure 4.31 connectivity is highest in Butter Beck and Baysdale Beck, which is probably because they are in steep sided valleys. However, upper Glaisdale Beck and the main Esk at Lealholm also have high connectivity, despite having gentle slopes adjacent to the channel. This may be due to inputs from floodplain ponding or drainage. Most of the main Esk has low lateral connectivity, as would be expected for reaches with a floodplain. However, channels in steep-sided valleys, such as parts of the Murk Esk and the lower part of Glaisdale Beck, have a low number of lateral inputs where a high number would be expected. This suggests that the presence of a floodplain does not always prevent connection of catchment sources to the flow and, conversely, that steep-sided valleys do not always result in high levels of connectivity. Part of the reason for the apparent low connectivity in steep-sided valleys might be that not all lateral inputs were recorded due to the difficulty in accessing and mapping these sections of the channel.

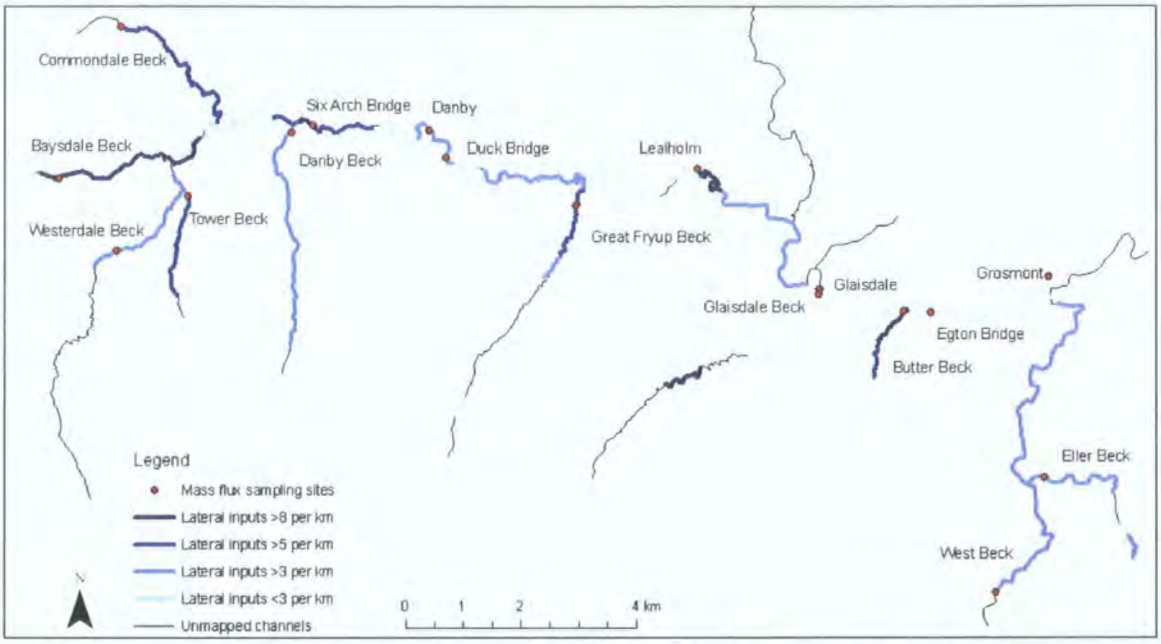

Figure 4.31. Density of lateral flow inputs to River Esk and major tributaries.

Furthermore, the number of lateral inputs is temporally variable, as it is dependent on the catchment wetness. Most of the catchment was mapped in February and March under similar conditions, during a cold, dry period with occasional snow. The density of catchment inputs recorded should not have altered during the mapping period, but is lower than if the catchment had been mapped during a wetter period. It was not possible to accurately map subsurface flow inputs from the catchment. However, it is known that drainage of the valley bottoms was carried out during the 1960s and 1970s as a result of an intensification of farming (personal communication with EA). Drainage was particularly extensive in Glaisdale and Great Fryup Dale. The headwater tributaries were drained less extensively but moorland gripping was carried out. The full extent of tile drains is unknown because individual farmers are responsible for their construction and maintenance. The significance of tile drains for sediment transfer is also unknown. However, the construction of tile drains in areas of floodplain is likely to have enhanced the lateral connectivity between catchment sediment sources and the channel in reaches where this would normally be low.

Sediment yields do not appear to be strongly linked to connectivity levels. High connectivity levels can be found in most tributaries, whereas yields from the tributaries vary. Butter Beck and Baysdale Beck both have high densities of catchment inputs but Butter Beck has a very high specific sediment yield, whereas Baysdale Beck has a low yield. High catchment sediment supply is dependent both on high sediment availability in the catchment and high levels of connectivity between sources and the channel; the availability of sediment sources within the catchment of Butter Beck may be higher than in Baysdale Beck. In addition, the high sediment yields in Butter Beck may originate not from catchment sources, but from channel sources. The greater extent of tile drains in Glaisdale and Great Fryup Becks, which are unaccounted for in Figure 4.31, may be of significance in causing higher specific suspended sediment yields in these tributaries, while the lower intensity of farming, and hence fewer tile drains, in the headwater tributaries may be partly responsible for the lower yields here.

Riparian land use is likely to have an impact upon the significance of non-channel sediment sources and may also affect channel bank stability. Figure 4.32 shows that the left and right banks have essentially the same land use patterns. Pasture is the dominant riparian land use in the catchment as a whole, and especially on the Esk above Glaisdale. This corresponds to the areas where a floodplain allows agriculture. Pasture is the dominant riparian land use in most of the tributaries (excluding the Murk Esk), also reflecting the existence of floodplains. Grazing intensities are generally not high in the Esk catchment. During mapping only one overgrazed field was observed adjacent to the channel, which was in the lower Murk Esk; runoff from exposed soil was supplying sediment to the river. The cold, dry weather which occurred during mapping may have concealed the true extent of sediment input to the river from runoff from areas of bare soil in the rest of the catchment. However, the main impact of riparian pasture on sediment supply to the Esk is to cause bank erosion from livestock poaching where the channel is unfenced (discussed above).

In the Murk Esk catchment, the Esk catchment below Glaisdale and parts of Glaisdale and Butter Becks, woodland is the dominant riparian land use. This is due to the steep sided valleys which are unable to support agriculture. As discussed above, falling trees were observed on steep valley sides, which may contribute to sediment input and to debris blockages in the channel, though on the whole woodland represents a low intensity land use which is unlikely to supply large amounts of sediment. In Baysdale, moorland is the dominant riparian land use. The low sediment yields from this tributary may be related to the low-intensity land use in the catchment. The occurrence of only one reach in the catchment with arable farming adjacent to the channel indicates that soil disturbance and erosion due to arable farming is not a significant sediment source.

A

B

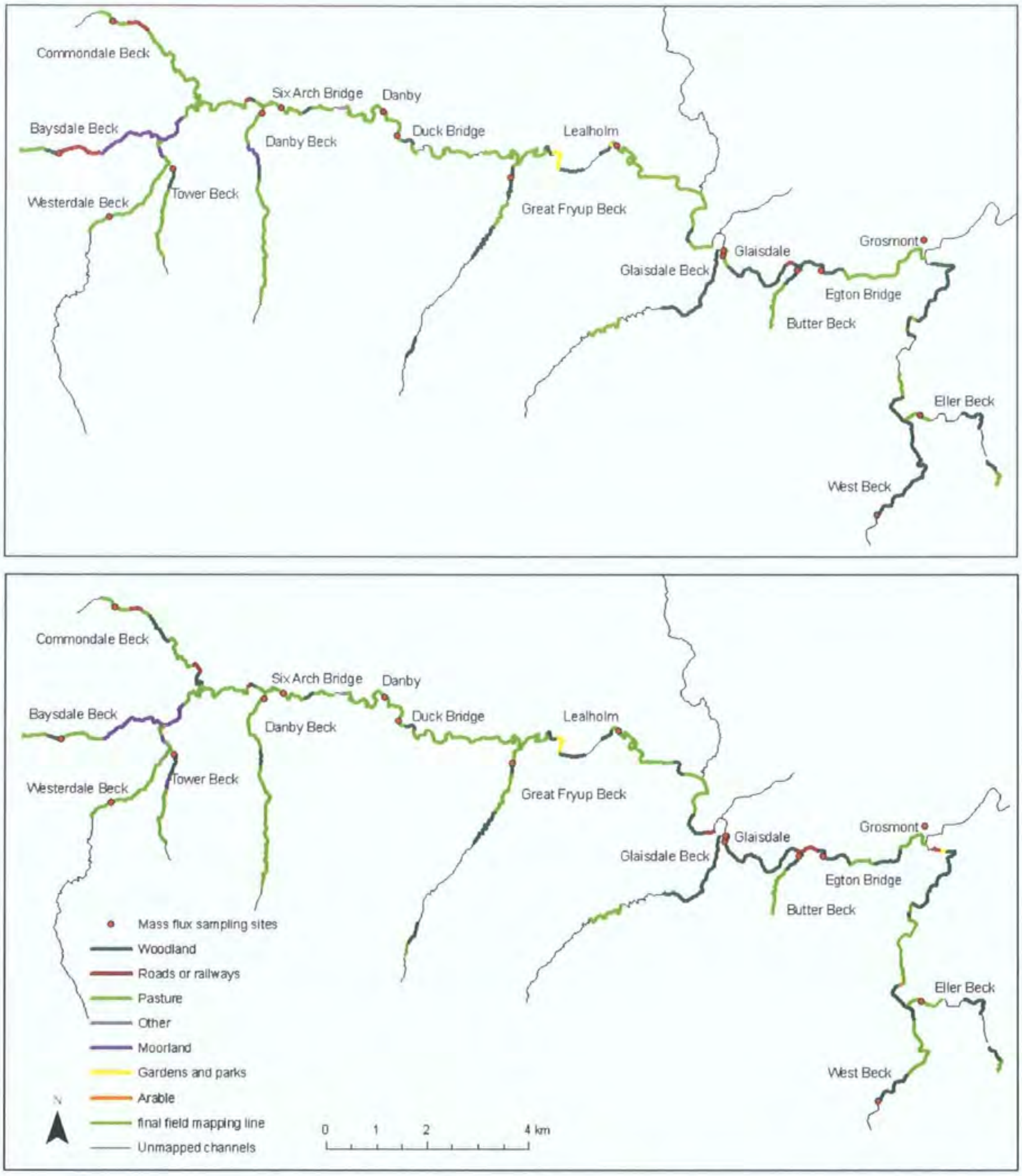

Figure 4.32. Riparian land use of River Esk and major tributaries – A) left bank; B) right bank.

4.4. Implications for suspended sediment supply and transfer

The spatial pattern of specific suspended sediment yields in the upper Esk catchment does not conform to the widely cited model of an inverse relationship between specific yield and catchment area. This general model assumes that the catchment configuration follows the conventional model of a downstream increase in floodplain width which, in the Esk catchment, has been shown not to be the case. In addition, the channel and catchment characteristics are highly variable on the main Esk, between and within tributaries. Variations are not always systematic because of the influence of the underlying geology and glacial drift, and because of variability in farming and land management practices in different parts of the catchment. This is likely to further confound any relationship between specific sediment yield and catchment area.

Instead of the hypothesised relationship, a different spatial pattern relating to suspended sediment yields and catchment and channel characteristics can be seen, whereby the catchment is divided into an upper and a lower section, the division occurring around Great Fryup Beck. In the upper part of the catchment sediment loads in the main Esk are greater than the total load input from tributaries (Figure 4.7). This shows that the main contribution of sediment to the river is from the main channel. Catchment mapping suggests that the main cause of this input is extensive slumping of high, sandy channel banks. Despite having potential for suspended sediment input from extensive bank erosion, poaching and higher catchment connectivity levels, sediment supply from the tributaries in the upper part of the catchment is low. This may reflect the lower channel bank height, lower intensity land use and possible lower extent of tile drainage.

In the downstream part of the catchment, sediment loads from tributaries account for the total increase in sediment loads at sites along the main Esk. This indicates that the tributaries are the dominant sediment source. This is partly due to the lower importance of channel bank sediment sources in the lower main Esk than the upper Esk. The high tributary yields may be due to more intensive land use and possible tile drainage in the valleys and also to the fact that these tributaries drain different drift geology to the other parts of the catchment. Recent channel management is the main cause of the high yields from Butter Beck.

The differences in channel and catchment characteristics in the upper and lower parts of the catchment are likely to affect the temporal dynamics of suspended sediment during storms. Important factors include the dominant type of sediment, the form of erosion, whether the supply is from within or outside the channel and the location of the sediment supply within the sub-catchment. These affect the mode of sediment delivery to the channel, its response to different flow and rainfall conditions and, hence, the temporal dynamics of suspended sediment behaviour. Chapter 5 will analyse temporal patterns of suspended sediment transport to determine how sediment originating from different source types responds to varying flow and storm conditions.

5. Temporal patterns of suspended sediment dynamics

5.1. Introduction

Temporal variability in suspended sediment dynamics is significant in most fluvial systems. The nature of this variability is dependent primarily on the flow regime and the sediment production processes. In many catchments a large proportion of the total suspended sediment load is transported in a very small fraction of the time (see Section 2.2.2). Therefore the entire flow and transport regime must be studied to gain a full understanding of the suspended sediment dynamics. Temporal variation in response to storms is of key interest in determining the linkages between sediment production processes, sediment transfer, SSC and sediment loads. The objectives of this chapter are firstly to examine the flow regime of the Esk and the overall variation in suspended sediment characteristics. Secondly evaluate the suspended sediment dynamics in relation to stage variation both within and between storms. Thirdly, analyse temporal trends in suspended sediment dynamics based on mass flux yields in relation to hydro-meteorological conditions.

5.2. Flow regime

Figure 5.1 shows the stage records for the two sites. The stage record at Grosmont is of lower resolution than the record at Danby because of a calibration problem with the pressure transducer (see Section 3.3.1). Nevertheless, the magnitude and timing of hydrological events is correct and both records show similar trends in stage over the study period. The river regime at both sites is characterised by periods of low flow interspersed with high discharges of a flashy nature. This is due to the steep sided catchment and peaty interfluves, which induce rapid delivery of water to the river. High flow events occurred throughout the monitoring period. The most extreme event during the monitoring period occurred on 22nd May when stage rose to 4.7 m at Danby and 2.3 m at Grosmont. Other significant flow peaks were generally between 2 and 2.5 m at Danby and around 1 m at Grosmont. The flow duration curves, constructed using the stage records (Figure 5.2), clearly show the episodic nature of the flow at both sites.

The majority of flows in the river are at a low stage; flows above 1 m occur for less than 10 % of the time. The narrow, steep-sided channel at Danby causes stage to increase more rapidly than at Grosmont, where the channel is wider and less steep-sided. Bankfull discharge is approximately 15 m^3s^{-1} at Danby (calculated from flow gauging), and 34 m^3s^{-1} at Grosmont (estimated from bankfull channel capacity).

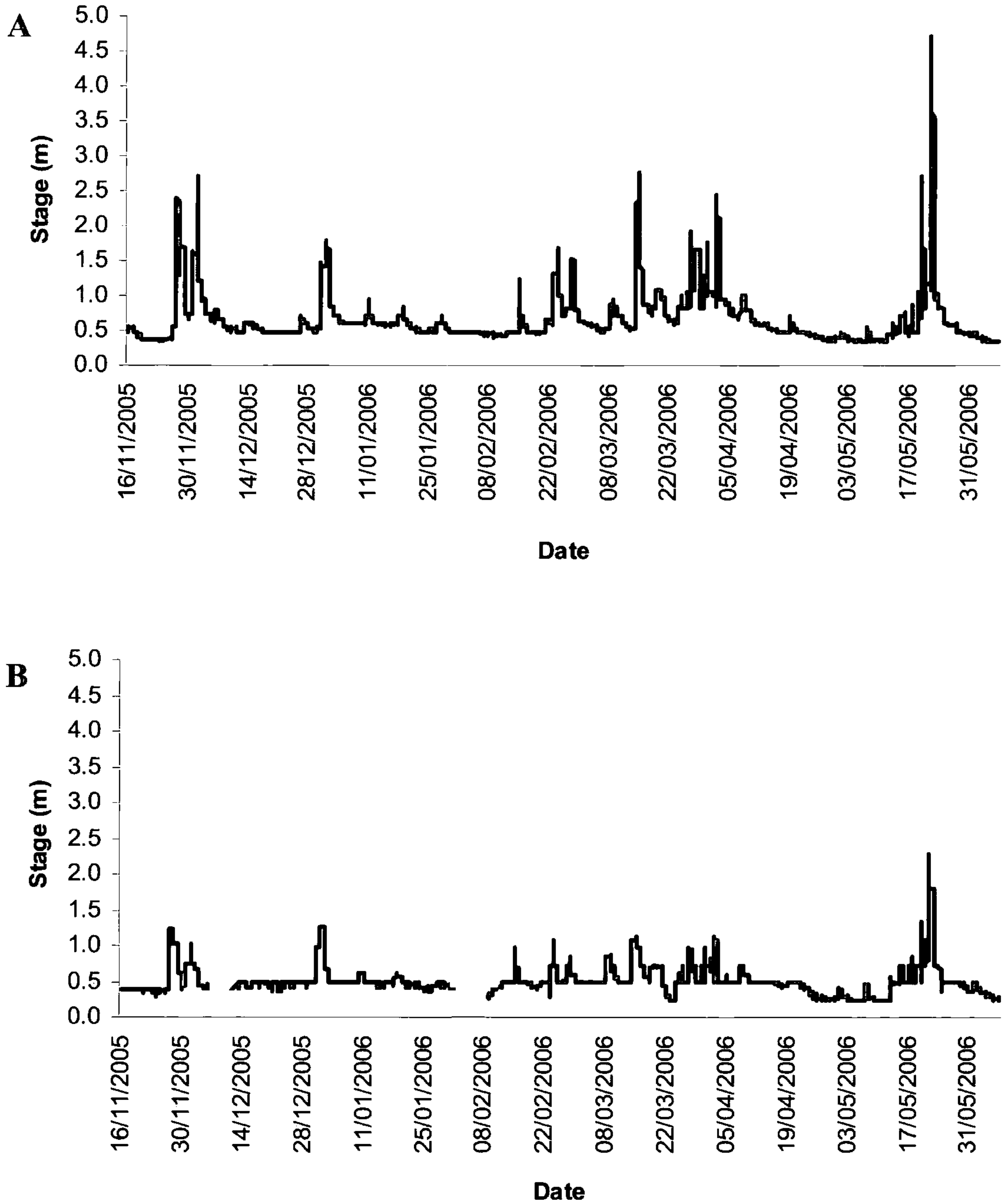

Figure 5.1. Stage records at A) Danby and B) Grosmont.

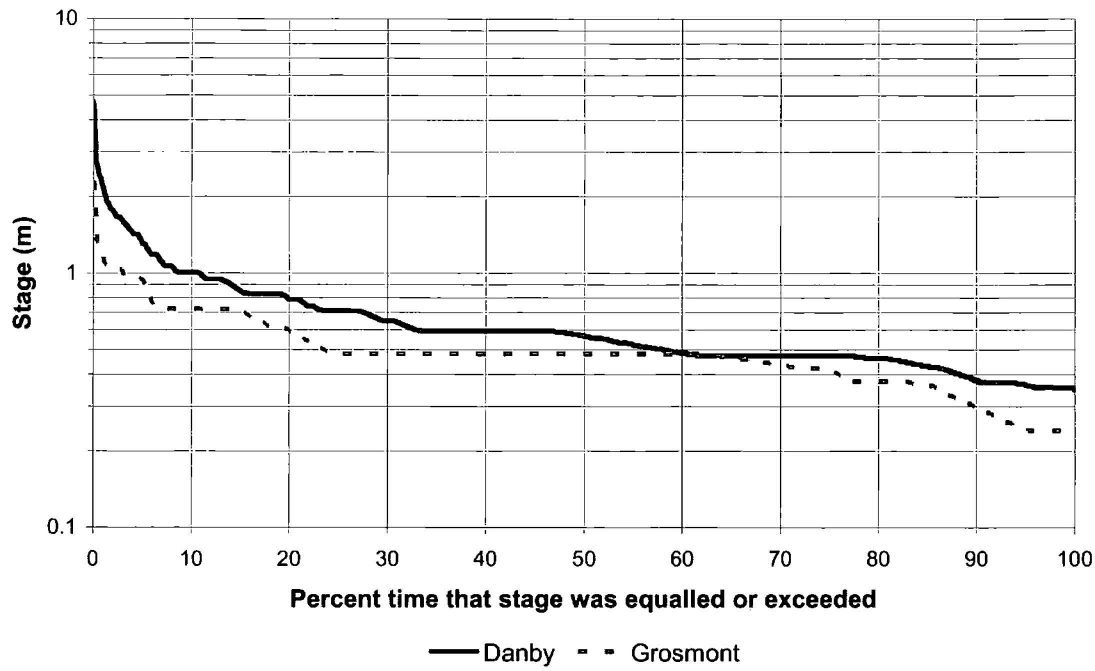

Figure 5.2. Flow duration curves for the Esk at Danby and Grosmont between November 2005 and June 2006, for 15 minute stage values.

Comparison of this data with the longer term record from Sleights (approximately 6 km downstream of Grosmont) shows that flashy flow peaks are a characteristic feature of the Esk and that high flow events occur at any time of year (Figure 1.5 A). Figure 1.5 (B) shows an episodic flow regime, comparable to Figure 5.2 (note differences in scale). Figure 1.5 (B) also indicates that during the winter (December to March) mean flows are higher than in the summer (June to September). However, the summer is characterised by some extreme events. The stage record obtained for the Esk in this study is characteristic of the general flow patterns observed in the Esk over longer timescales. The flashy nature of the discharge of the Esk suggests that suspended sediment transport is likely to be episodic. The rest of this chapter will explore the dynamics of suspended sediment transport and how they relate to the flow characteristics.

5.3. Suspended sediment characteristics

5.3.1. Suspended sediment-turbidity relationship

Suspended sediment sampling on the Esk comprised discrete samples taken during storm events, while a quasi-continuous record of turbidity was obtained from monitoring at Danby and Grosmont. Turbidity has been shown to be a reliable indicator of SSC (Section 3.2.3) and can therefore be used as a proxy for SSC in periods where water samples were not taken.

Figure 5.3 shows the relationship between SSC and turbidity (measured in nephelometric turbidity units, NTU) for the Esk which has been derived using data from two storm events at Danby and three at Grosmont. Previous research has found that relationships between suspended sediment and turbidity are often site and storm specific because of variations in the importance of different sediment sources. All the suspended sediment data used are from March, except for one set of samples from a storm in May at Grosmont. The relationship for the May samples does not differ significantly from the March samples so the same relationship was used for both. When plotted separately it was found that the relationships between SSC and turbidity at Danby and Grosmont were similar, so it was decided to group the data to give one relationship for both sites. This had the advantage of extending the overall range of the data and thus reducing the need for extrapolation when calculating higher SSCs. The R-squared value for the entire data set is 0.93 and shows a strong positive relationship, implying that spatial and temporal variations in the turbidity-SSC relationship for the Esk are not significant.

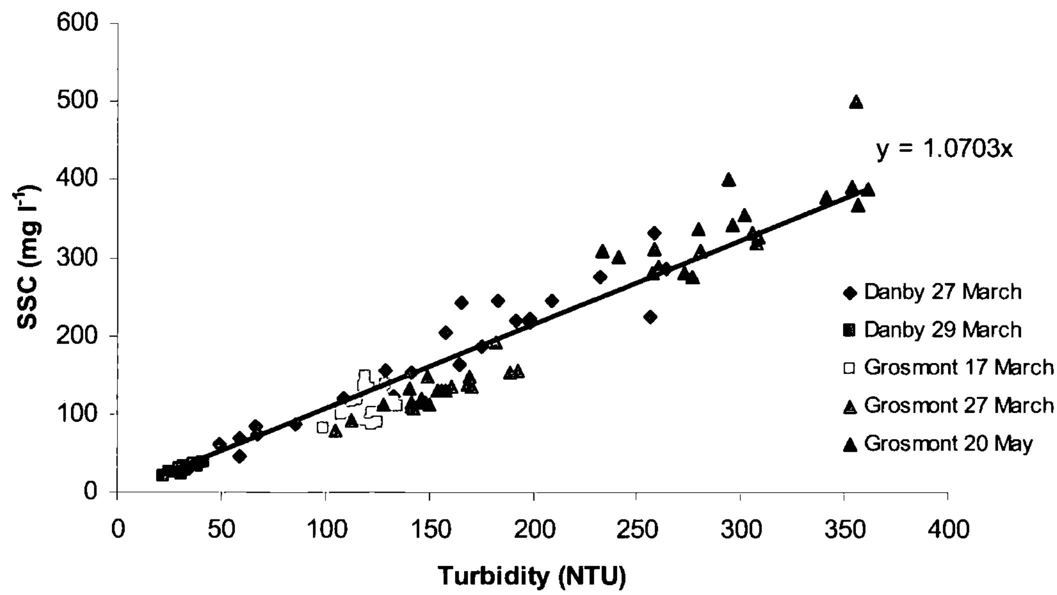

Figure 5.3. Relationship between turbidity and SSC with intercept of best fit line set at zero. The colour of the points relates to data from different storms from Danby and Grosmont.

At values of turbidity above the range of data used for the calibration (362 NTU), the relationship is still likely to hold because the turbidity probe used specifies that a linear relationship exists up to 1000 NTU. However, it should be noted that these are extrapolated values. The y intercept of the initial regression line was at -23.6 mg l^{-1}, showing that low levels of turbidity occur in the absence of suspended sediment. This turbidity could be due to water colour or bubbles. The intercept value of the regression line was considered small enough that in order to avoid negative SSC being calculated from low turbidity values, the intercept was set at zero. This had the effect of reducing the R-squared value from 0.93 to 0.92, thus maintaining a strong relationship.

5.3.2. Suspended sediment concentrations

Peak SSC at Danby and Grosmont during storms was typically between 100 and 500 mg l^{-1}. The maximum concentration sampled at Danby was 556 mg l^{-1}, while at Grosmont it was 500 mg l^{-1}. At Grosmont the maximum concentration calculated from the turbidity record was 1063 mg l^{-1}, although this is an extrapolated value (discussed in Section 5.3.1). At low flows sampled SSC was less than 1 mg l^{-1}. This large range in SSC shows the episodic nature of suspended sediment transport in the Esk. The values of maximum SSC are typical of other upland catchments in the UK, where maximum concentrations in sampled storms are commonly between 400 and 500 mg l^{-1} (e.g. Wood, 1977; Carling, 1983; Burt and Gardiner, 1984; Smith *et al.,* 2003).

The analysis of SSC in the following sections assumes that suspended sediment is well mixed within the channel cross section. Water samples were taken across the channel at Danby on two occasions to test whether this assumption is valid. The first set of samples was taken on 20th May, during a rising hydrograph limb, when stage was 0.9 m. The second set of samples was taken on 1st June when stage was 0.5 m (Figure 5.4). On 20th May the samples taken closest to the bank had the highest SSC. This may be because much suspended sediment is derived from entrainment of channel bank sediment. The intake hose for the automatic water sampler was positioned close to the channel bank, so concentration values from automatic samples may be slightly higher than the cross sectional mean. However, at higher concentrations and discharges suspended sediment is likely to become better mixed so that cross sectional variation in SSC is insignificant

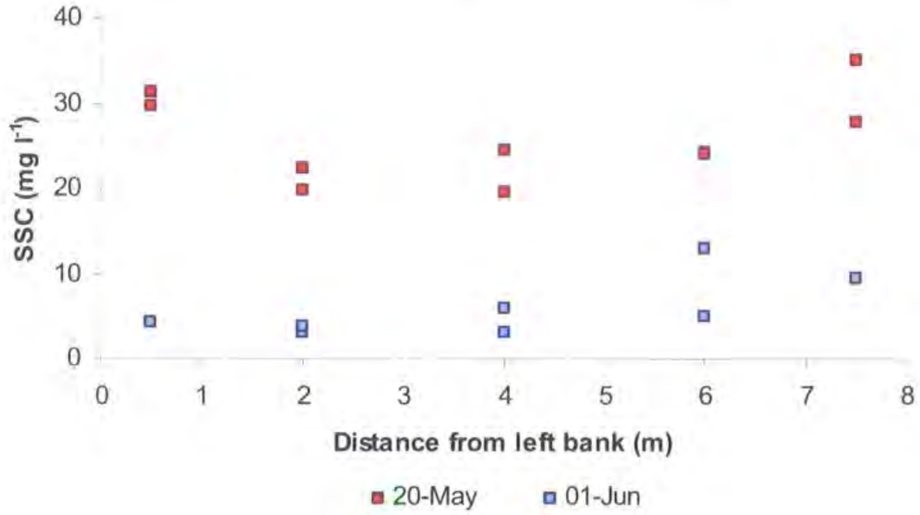

Figure 5.4. Cross sectional variations in SSC at Danby, sampled on 20th May and 1st June.

5.3.3. Suspended sediment concentration-stage relationship

Relationships between SSC and stage were plotted for Danby and Grosmont (Figure 5.5). At both sites relationships are weak and display scatter. Grosmont shows more scatter than Danby, but this is partly because a larger amount of data was included in the plot. The loops that can be observed in the distribution of points relate to hysteresis in individual storm events, which will be discussed in Section 5.4. The scatter in the relationships shows that suspended sediment transport is not simply a function of discharge.

A

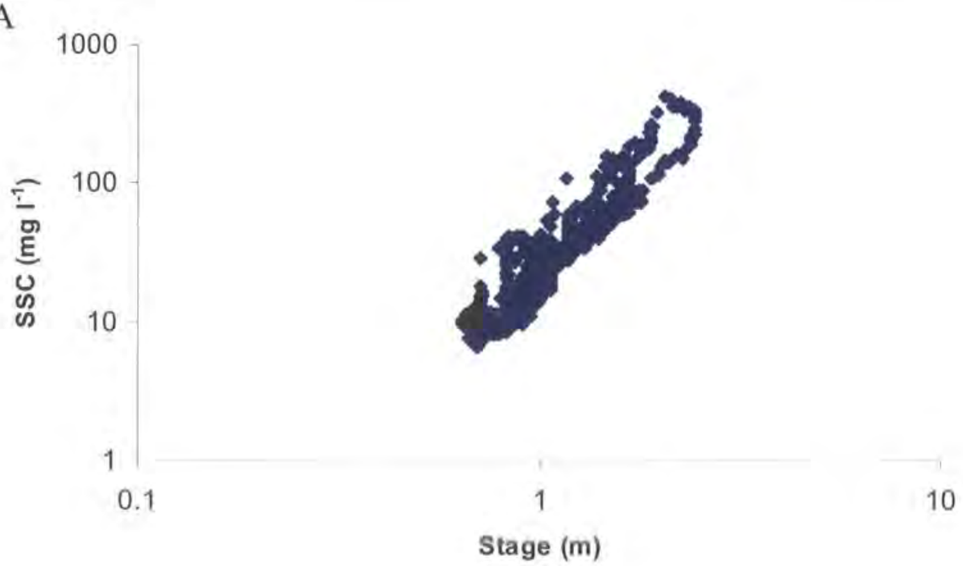

Figure 5.5 (A) Stage and SSC relationship at Danby (March-April 2006).

B

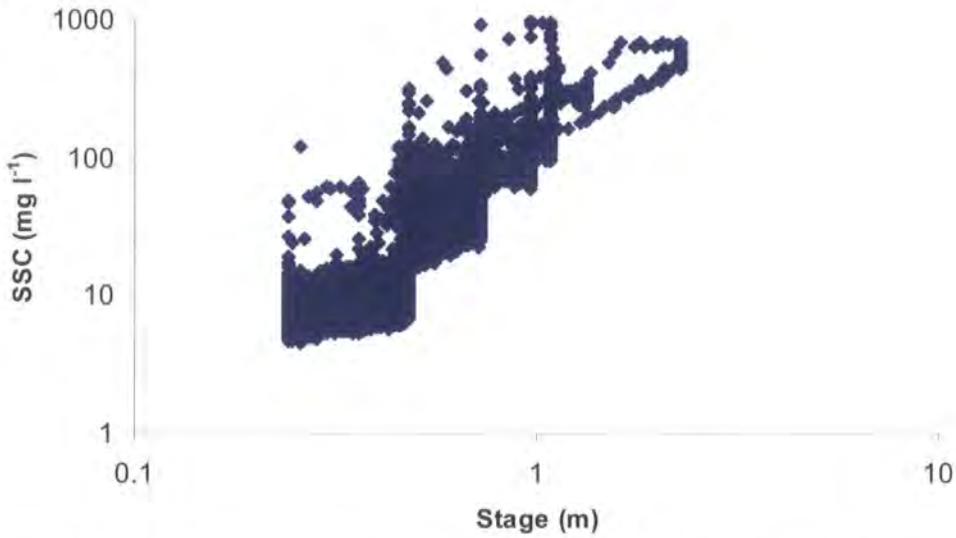

Figure 5.5 (B) Stage and SSC relationship at Grosmont (March-June 2006).

5.4. Suspended sediment dynamics

The previous section showed that SSC is not directly related to discharge. Variations in SSC can be attributed to variations in sediment supply. Therefore an understanding of the behaviour of suspended sediment within and between storms can help infer the dynamics of the supply and temporal variations in the availability of sediment.

5.4.1. Between storm suspended sediment dynamics

In this study the short period of monitoring is insufficient to allow examination of seasonal patterns of suspended sediment dynamics and hence the analysis will focus on short-term sediment exhaustion patterns. The stage records show five main high-flow periods interspersed with some smaller flow peaks (Figure 5.1). Due to the length of the turbidity record, flow events earlier than February could not be analysed. At Grosmont three series of storms were analysed. These were in February, March-April and May. At Danby, due to technical difficulties with the turbidity probe, the turbidity record is only reliable for one series of storms, which was from late March to early April. The storm sequences analysed are summarised in Table 5.1.

Table 5.1. Summary of storm sequences within which SSC dynamics were analysed.

Sequence	Site	Dates (2006)	Number of flow peaks
1	Grosmont	15-28 February	3
2	Grosmont	15 March-8 April	10
3	Grosmont	15-22 May	4
4	Danby	26 March-3 April	6

It was hypothesised that sediment exhaustion would occur between flow peaks in a sequence, resulting in lower SSC peaks relative to the size of stage peaks in later events. This is clearly evident in storm sequence 1 (Grosmont, February 2006) (Figure 5.6), where the second flow peak, despite being of a greater magnitude than the first peak, has a much lower peak SSC associated with it.

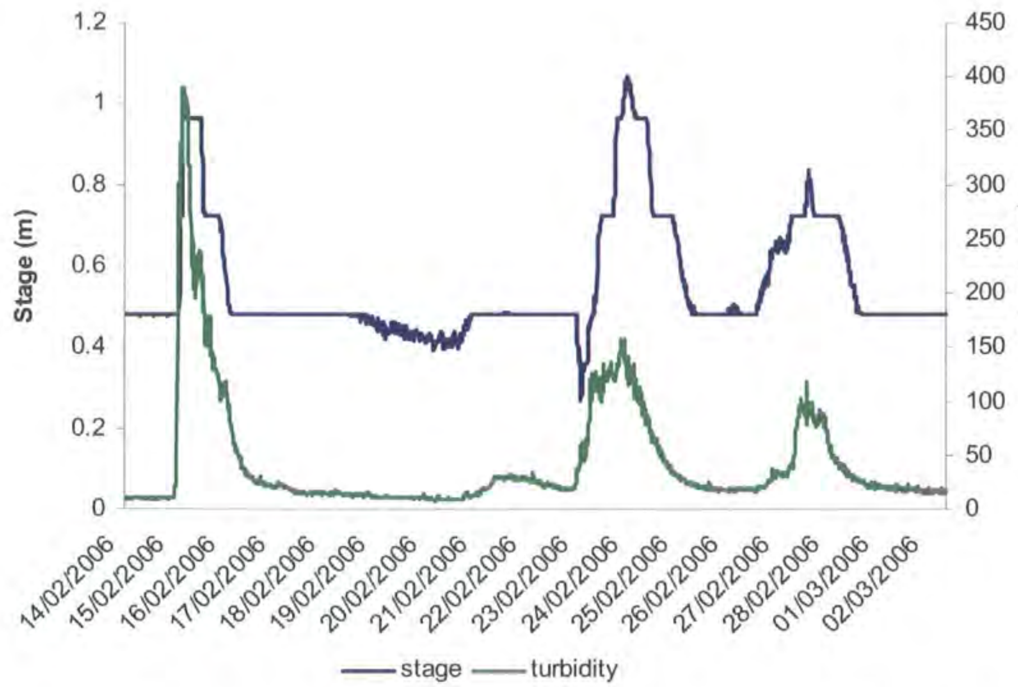

Figure 5.6. Flow and SSC fluctuations during storm sequence 1, Grosmont, February 2006.

Storm sequences 2 (Grosmont) and 4 (Danby) occurred over the same time period, between late March and early April (Figure 5.7). Progressively lower SSC peaks are evident in the sequence, except for the event on 3rd April, which produced a high peak SSC value at both locations, despite being the sixth major flow peak in the sequence. The associated stage peak was the highest in the sequence at both sites, which suggests that it had a greater capacity to mobilise sediment which was unavailable to lower magnitude flows. This may have been through a local large-scale bank failure or a high input from non-channel sources resulting from high catchment wetness. This example shows that sediment inputs during a sequence may increase sediment availability to later flows, thus reducing the exhaustion effect.

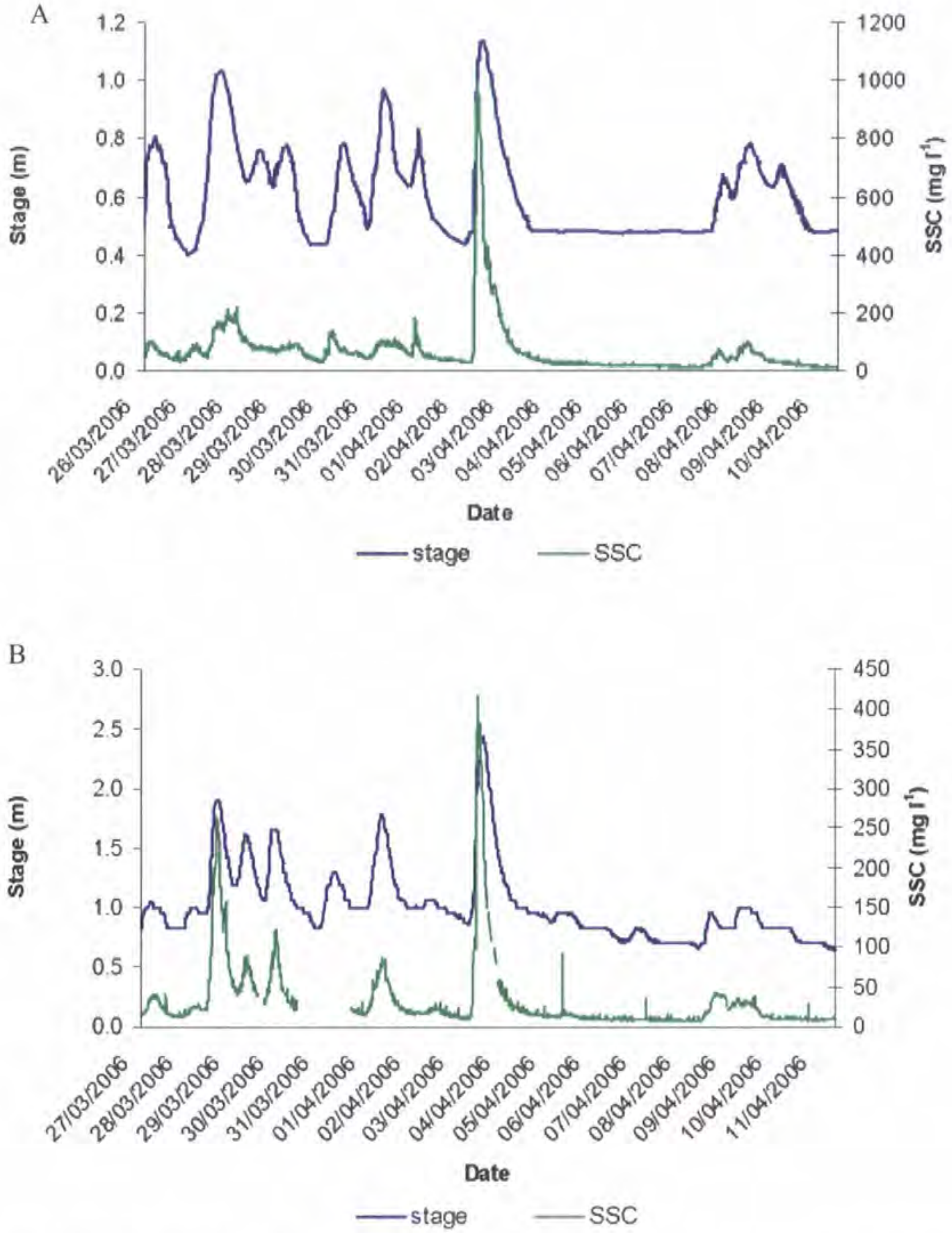

Figure 5.7. Flow and SSC fluctuations during March/April 2006: A) storm sequence two, Grosmont; B) storm sequence four, Danby.

Figure 5.8 shows suspended sediment and stage peaks during storm sequence 3 (Grosmont, May 2006), where sediment exhaustion effects are not apparent. Later flow peaks are higher than earlier ones, so are able to access and mobilise sources of sediment unavailable to the lower peaks. This would reduce any sediment exhaustion effect caused by the earlier flow peaks. Wetting up of the catchment during the sequence may also have enabled the connection of a greater number of non-channel sources to the channel and, hence, higher sediment input.

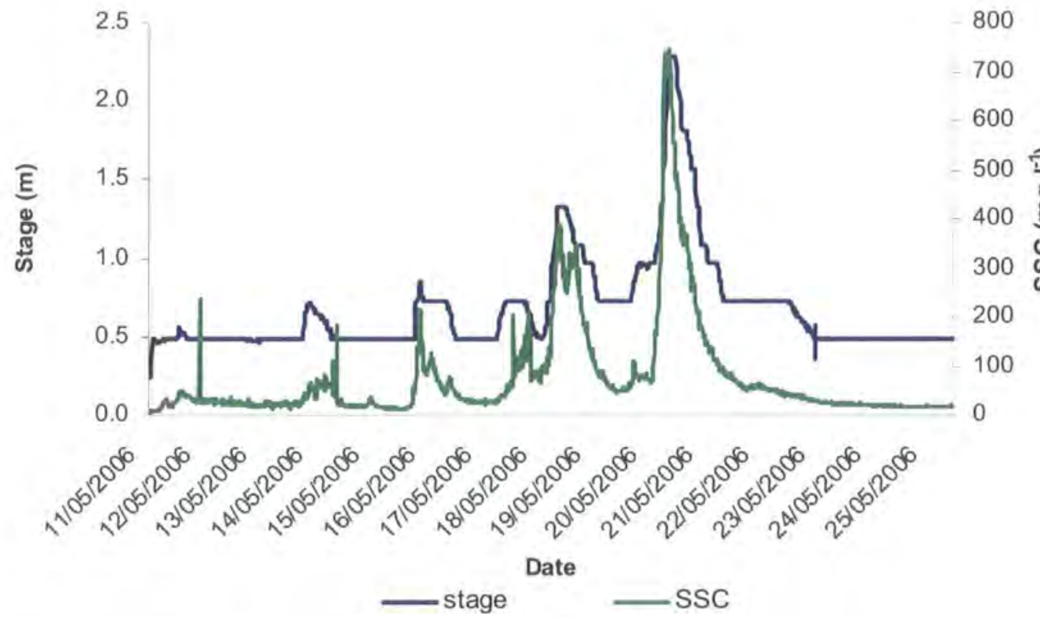

Figure 5.8. Flow and SSC fluctuations during storm sequence three, Grosmont, 15th-22nd May 2006.

While sediment exhaustion effects between flow peaks do occur, Figures 5.7 and 5.8 suggest that the sediment exhaustion effects may be more dependent on the amount of time since a flow of equal or greater magnitude than simply on the amount of time since the last flow peak. A longer time period between high flows allows more time for the accumulation of sediment, which then becomes available to the flow when stage increases. The variability in the between-storm dynamics of SSC in different storm sequences suggests that sediment accumulation is not constant in time and space. In particular this may be because i) sediment accumulation does not occur at a constant rate over time but occurs through the occurrence of episodic events, such as bank failure, as suggested by Figure 5.7; ii) the rate of sediment accumulation may not be spatially constant, due to the operation of different sediment production processes; iii) the rate of sediment accumulation is dependent on weathering and erosion processes such as freeze-thaw or desiccation, which operate favourably in certain conditions.

5.4.2. Within-storm suspended sediment dynamics

Within-storm suspended sediment dynamics were investigated to determine whether they can be related to variations in storm characteristics, sediment supply and catchment conditions. This should allow further inferences about dominant sediment input and transport mechanisms to be made. Previous research suggests that within-storm suspended sediment behaviour is dependent on the nature of the rainfall and flow during the event, the antecedent conditions, the location of the dominant sediment sources and the relative speeds of the flood and suspended sediment peaks (Klein, 1984; Prowse, 1984; Brasington and Richards, 2000; Seeger *et al.,* 2004; Armstrong, 2005). This will form the basis for the analysis of within-storm sediment dynamics in the Esk. In supply limited systems, similar to the Esk, clockwise hysteresis is typically dominant and is indicative of sediment exhaustion during the storm (Armstrong, 2005).

The samples of suspended sediment which were taken at high resolutions through storms provided the data for this analysis, and were supplemented by continuous turbidity measurements transformed to SSC values (described in Section 5.3.1). Fourteen different storm events were analysed in total (Figure 5.9). Five events were common to Danby and Grosmont, with a further seven events analysed only at Grosmont and two only at Danby.

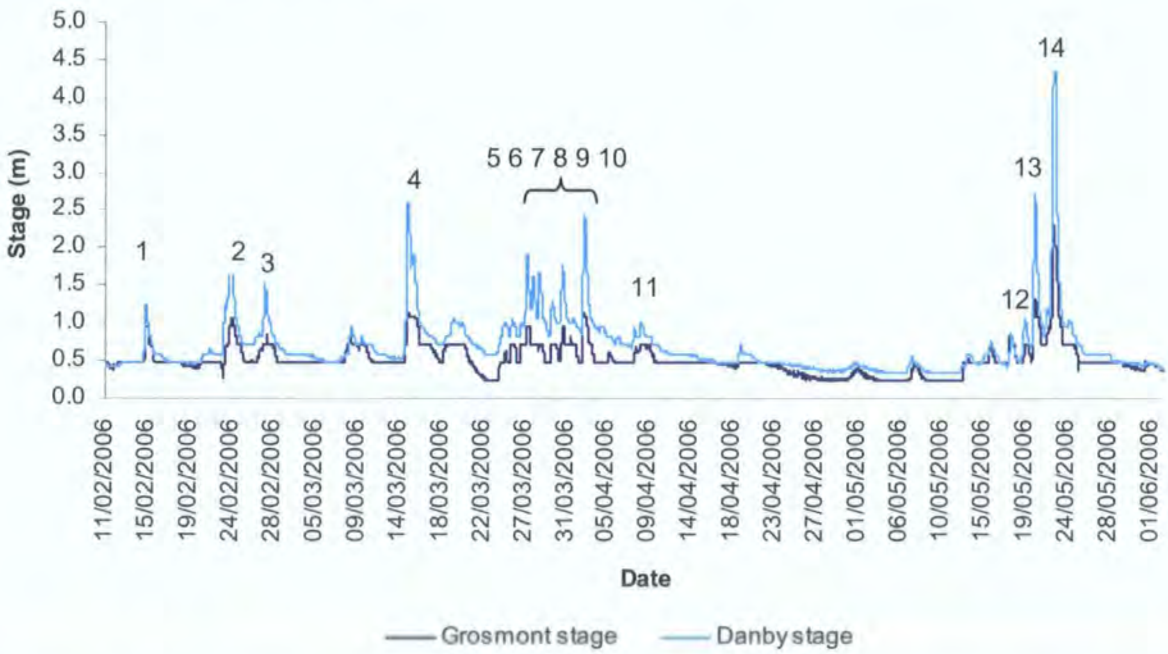

Figure 5.9. Stage records at Danby and Grosmont showing the storm peaks analysed for within-storm suspended sediment behaviour.

Each flow peak was classified according to its form of hysteresis. Of the twelve flow peaks analysed at Grosmont, six displayed clockwise hysteresis, one displayed multiple clockwise loops, two displayed anticlockwise hysteresis and three were complex, comprising loops of different directions. At Danby three hysteresis events were clockwise, three were anticlockwise and one event had a linear relationship between stage and SSC. Although clockwise hysteresis was the most common type, the occurrence of other types of hysteresis shows that within-storm suspended sediment behaviour in the Esk is variable and that sediment supply and transport processes are not the same for every event.

5.4.2.1. Analysis of storm events

Clockwise hysteresis occurred in events 1, 2, 4, 8, 10, 11 and 14 at Grosmont and events 5, 10 and 13 at Danby. Clockwise hysteresis is a result of higher SSC on the rising than on the falling limb of the hydrograph, for equivalent values of discharge (Figure 5.10).

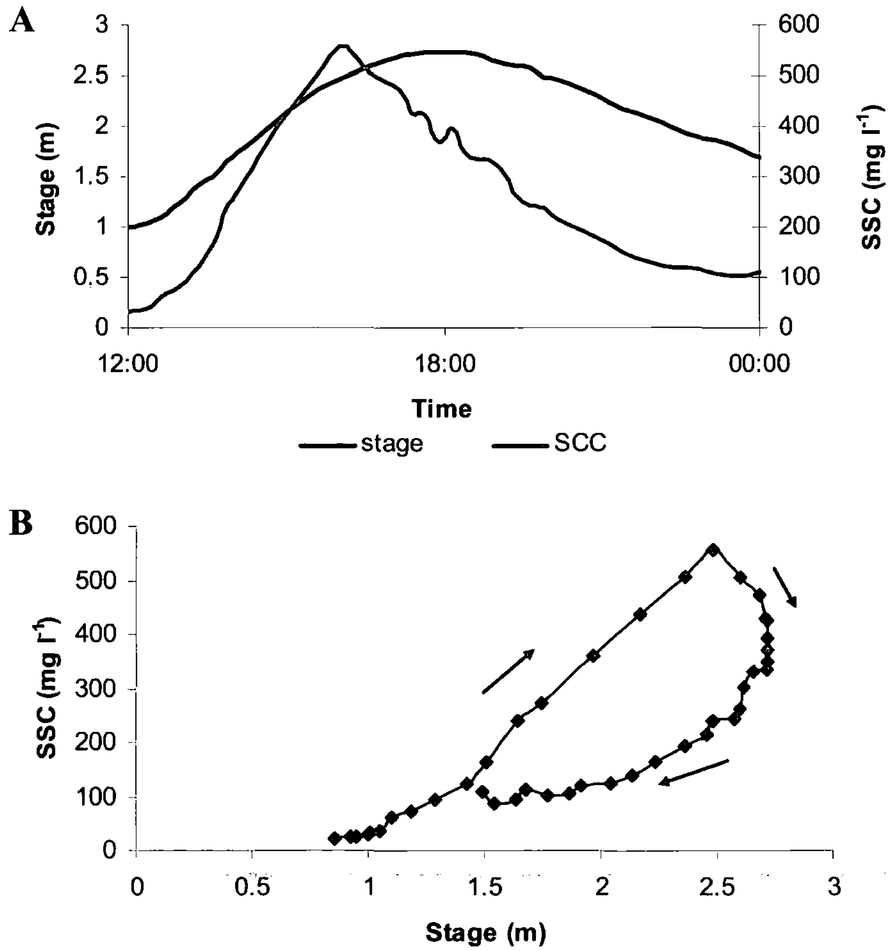

Figure 5.10. Suspended sediment behaviour at Danby, showing clockwise hysteresis, 20th May 2006: A) flow and SSC graph; B) hysteresis plot.

This implies rapid delivery of sediment sources to the flow at the beginning of the event. Dominant sediment sources in these events are therefore close to or within the channel. Observations of the main Esk at low flow showed that sediment is stored within the channel, both on the bed and as slumped material from the banks (Figure 5.11 A). The upper part of the main Esk and many tributaries, such as Butter Beck, also had significant storage of fine sediment in parts of the channel (Figure 5.11 B) (Section 4.3.2). This suggests that mobilisation and flushing of these readily available within-channel sediment sources by the rising flow is likely to be the cause of the high concentrations at the beginning of the event. The lower concentrations on the falling limb show that this sediment source becomes exhausted later in the storm. Runoff from distant parts of the catchment arrives in the main channel later in the event and contributes to a greater proportion of flow on the falling limb. Within-channel sediment sources, therefore, appear to be the most important sources in events which display clockwise hysteresis.

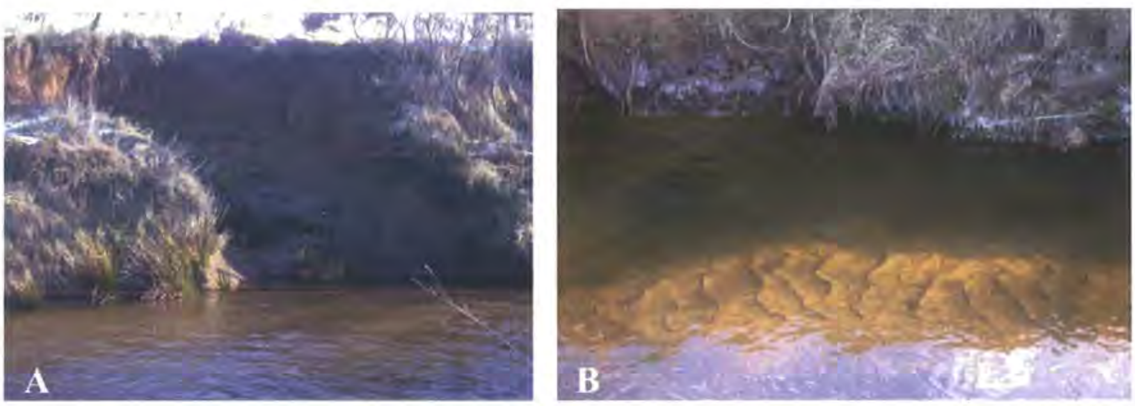

Figure 5.11. Examples of within-channel sediment supplies in the main Esk near Danby: A) exposed material from bank failure; B) fine sediment stored on channel bed.

At both sampling sites all the events with clockwise hysteresis, except one, occurred at least 12 days after a flow of greater magnitude. This supports the idea that clockwise hysteresis occurs due to the flushing of stored within-channel sediment through the system. A longer period of time between storms allows a greater supply of sediment to accumulate in the channel by processes such as subaerial weathering of banks, slumping of banks and deposition of sediment on the channel bed by low magnitude flow events. This sediment is then available to be mobilised on the rising limb of the next high flow. At Danby one clockwise event (event 8, 30th March) occurred one day after a higher flow. This is unusual and indicates a rapid accumulation of in-channel sediment, which could have been due to a sudden input such as from bank failure or because the low magnitude event which occurred one day before the event increased sediment availability by depositing sediment in the channel.

In total five events showed anticlockwise hysteresis. These were 5 and 7 at Grosmont and 6, 7 and 12 at Danby. Events 6 and 7 (28th and 29th March) occurred one day apart during a series of flow peaks. The events occurred one and two days after a peak of higher discharge, and all three of the peaks analysed had less than 0.6 m increases in stage (Figure 5.12). The lower SSC in these events, compared to events with clockwise hysteresis, indicates that sediment sources were less readily available to the flow. Lower concentrations of suspended sediment on the rising limb show that flushing of within-channel sources is not important. This is probably because of an exhaustion of sediment supplies by the earlier flow peaks. Sediment from a distant source, which arrived later in the event, may have caused the later peak in SSC (also suggested by Brasington and Richards (2000) as a hypothesis for anticlockwise hysteresis).

The literature suggests that anticlockwise hysteresis occurs when high catchment wetness allows connection of distant catchment sediment sources to the channel (Jeje *et al.,* 1991; Seeger *et al.,* 2004; Armstrong, 2005). Precipitation totals in the 72 hours preceding anticlockwise events 6 and 7 were above average (15 and 16 mm respectively) so catchment wetness and, hence, connectivity are likely to have been high. In these events sources of sediment from other parts of the catchment were probably of greater importance than sources near or within the channel. The much lower peak SSC in events where non-channel sources dominate, compared to clockwise events where in-channel sources dominate, confirms that over the longer timescale most of the sediment supplied to the Esk comes from within-channel sources and that non-channel sources are of lower importance.

Event 5 (27th March) at Grosmont also shows anticlockwise hysteresis. It has two flow peaks, with suspended sediment peaking after each. This effect may be due to sediment exhaustion by a large peak 12 days prior to the event and also because stage only increased by 0.24 m, which may not have been sufficient to induce flushing of any stored sediment. Anticlockwise hysteresis in event 12 (18th May) at Danby cannot be attributed to sediment exhaustion, as there had not been a higher flow event for 39 days. There was no rainfall in the 24 hours preceding the event, so catchment connectivity is likely to have been low. The low peak SSC (55 mg l^{-1}) indicates that this event did not transport large amounts of stored sediment. The main reason for this is probably the low peak stage (0.87 m) which did not reach a sufficient threshold to mobilise sediment. The event occurred in May when channel banks had higher vegetation cover than in winter and vegetation cover in the catchment is also likely to have been higher. The vegetation may have protected any bare sediment and raised the flow threshold needed for sediment mobilisation.

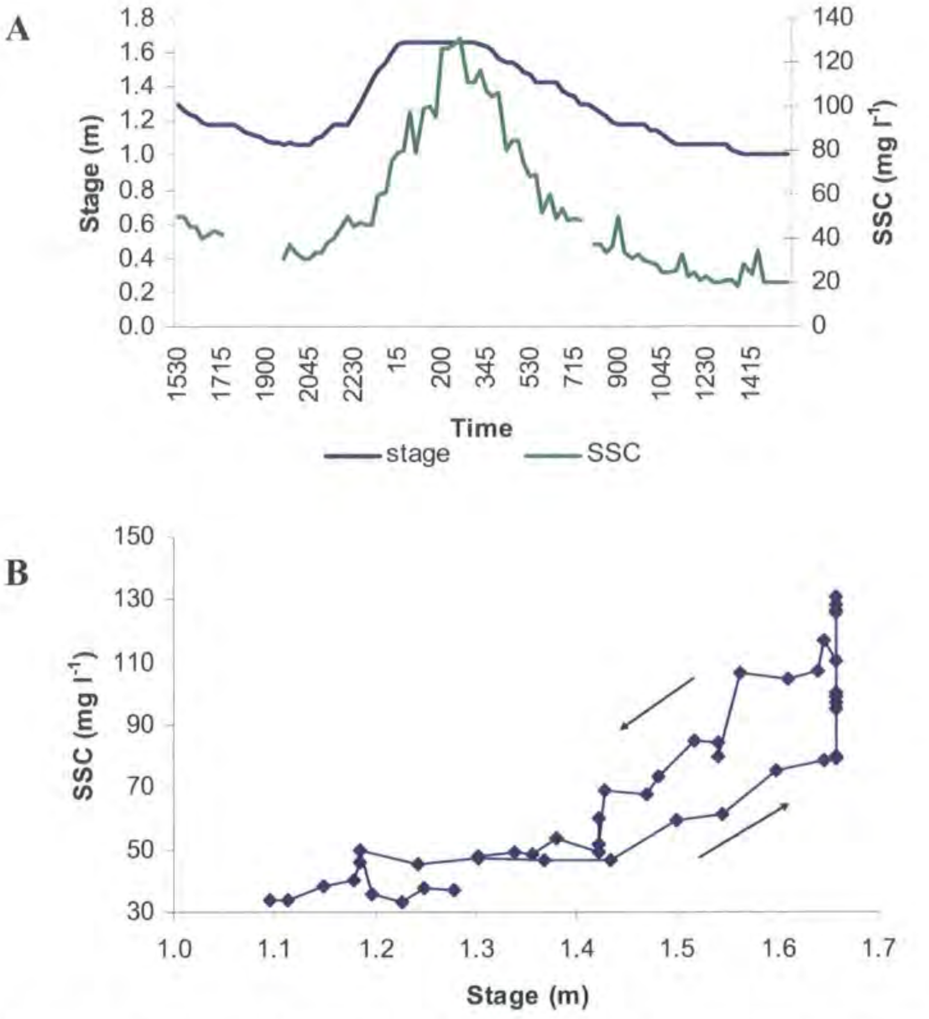

Figure 5.12. Event 7, 29th March, at Danby, showing anticlockwise hysteresis: A) flow and SSC graph; B) hysteresis plot.

Three storm events at Grosmont showed complex hysteresis patterns. In event 3 (28th February) suspended sediment and stage peaked simultaneously, but SSC remained high and had a second peak during the falling limb of the hydrograph. This shows that the later input of sources was of greater importance than the initial flush. The low peak SSC indicates in-channel sediment supplies were probably exhausted by the two storms which occurred before this event and that this event is similar to anticlockwise events 6 and 7 at Danby.

Event 13 (20th May) (Figure 5.13) shows simple clockwise hysteresis at the start of the event, probably associated with flushing of stored sediment. It is complicated by a second, smaller suspended sediment peak on the falling limb, which is not associated with a second flow peak or with a second rainfall event. The sediment in the second peak probably originated from a different source to the sediment in the main peak. Suggested causes for this are i) input from a local bank failure occurring later in the storm; ii) input from a source of sediment originating in a distant part of the catchment, with a longer travel time; iii) the later arrival of a suspended sediment peak from the Murk Esk, a large tributary (catchment area 80 km^2), which enters the Esk just above Grosmont. However, in the third scenario we might expect to see a later flow peak from the Murk Esk, associated with the suspended sediment peak, which is not the case.

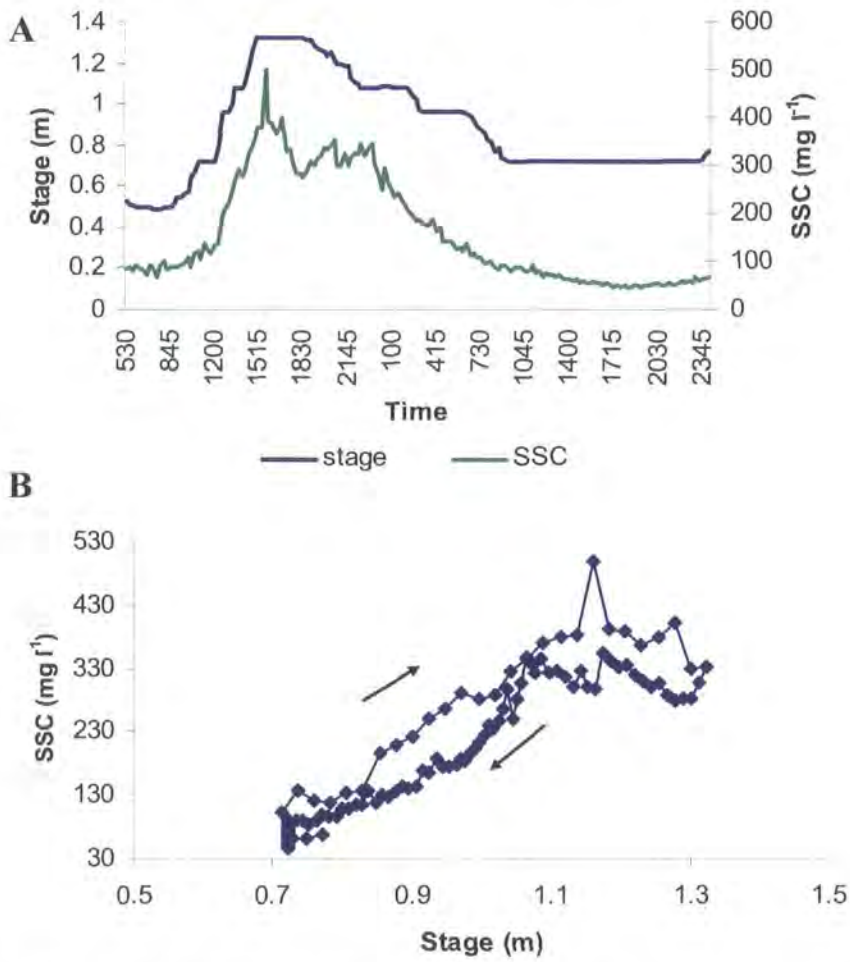

Figure 5.13. Event 13, 20th May, at Grosmont, showing secondary suspended sediment peak on the falling limb of the hydrograph: A) flow and SSC graph; B) hysteresis plot.

In event 9 (31st March) at Grosmont (Figure 5.14) SSC in the first peak is low and forms an anticlockwise loop. This can be attributed to the same causes as for the anticlockwise loops in event 5. However, SSC peaks again, before the second flow peak, resulting in a clockwise loop. While the second flow peak is lower, the second suspended sediment peak is significantly higher than the first. This is unusual because sediment exhaustion effects are usually more pronounced in later flows. The low SSC in the first peak clearly shows that sediment is not initially abundant. A period of rainfall at Grosmont occurs just before the second suspended sediment peak. The intensity of this rainfall may have been responsible for mobilising a new, non-channel source of sediment. Alternatively local bank failure could have occurred during the latter stages of the first peak, which provided a newly available source of within-channel sediment for the second flow peak. The second explanation seems more plausible, given the significant increase in SSC. The spiky, symmetrical nature of the second peak suggests a sudden input of sediment which is rapidly entrained and exhausted, such as might be expected from a bank failure.

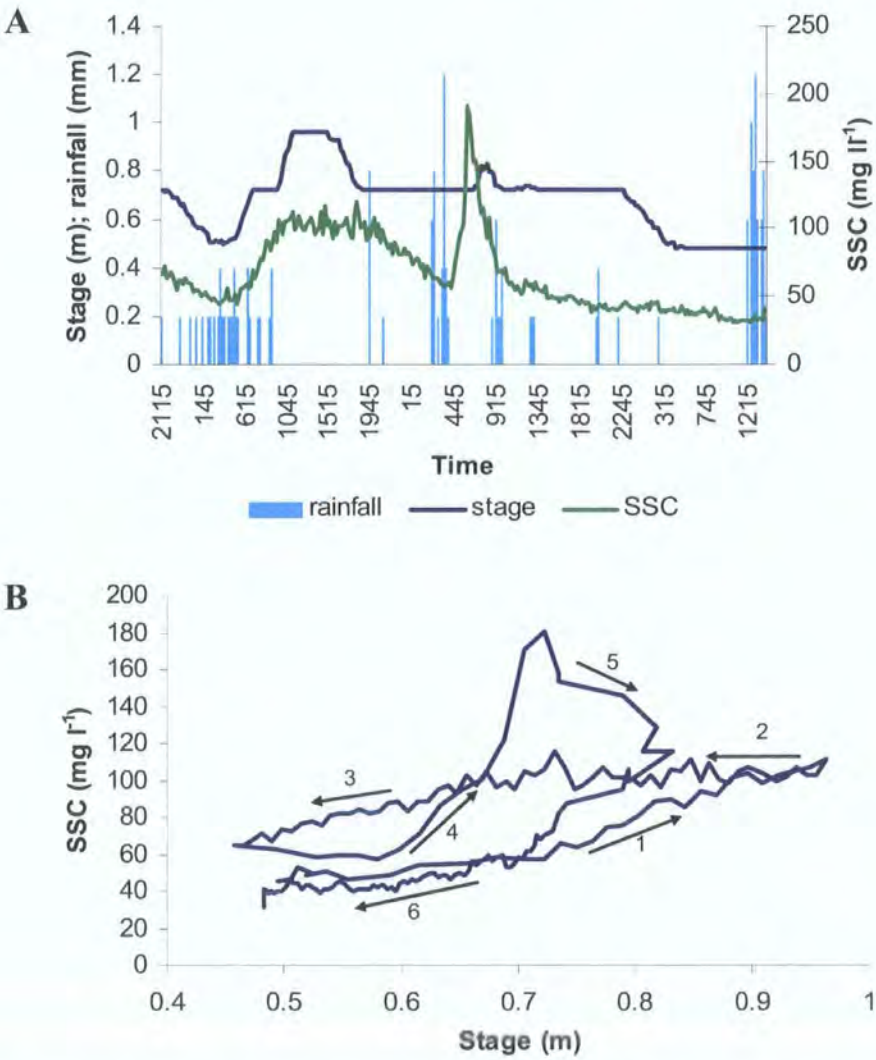

Figure 5.14. Event 9, 31st March, at Grosmont showing a complex suspended sediment behaviour response: A) flow, rainfall and SSC graph; B) hysteresis plot.

Event 9 also displayed unusual suspended sediment behaviour at Danby (Figure 5.15). Stage and suspended sediment have approximately synchronised peaks and similar spread and skewness, which results in a linear relationship between the variables. Linear relationships are unusual but have sometimes been observed in very short events with high sediment availability, where exhaustion does not occur (Wood, 1977; Jeje *et al.*, 1991). However, peak SSC in event 9 is low. Sediment sources are likely to have been exhausted by the four events preceding event 9. The lack of within-storm exhaustion implies a low but continuous supply of sediment to the flow, for example from fluvial erosion and entrainment of channel bank and bed sediment.

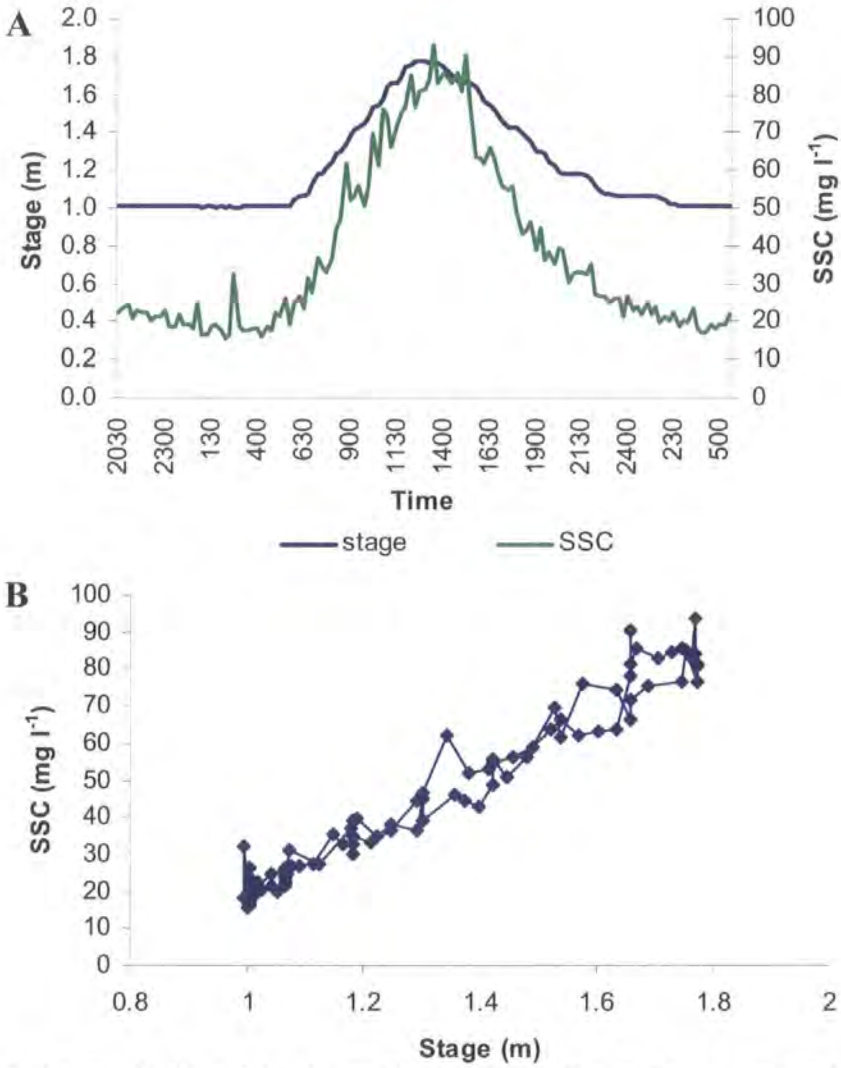

Figure 5.15. Event 9, 31st March, at Danby, showing a linear suspended sediment response to stage: A) flow and SSC graph; B) hysteresis plot.

5.4.2.2. Comparison of hysteresis at Danby and Grosmont

In the events where records for Danby and Grosmont exist, comparison of the hysteresis shape at each site during the same event will help show whether the same processes are responsible for sediment transfer at both sites. In event 7 (29th March) both sites show anticlockwise hysteresis and both sites have low peak SSC. In event 10 (3rd April) both sites showed clockwise hysteresis, associated with high SSC and a high flow peak.

Hysteresis in event 13 (20th May) was clockwise at Danby and initially clockwise at Grosmont, associated with flushing of stored in-channel sources. However, the Grosmont event was complicated by a second, smaller SSC peak on the falling limb. As this peak is only evident at Grosmont, it can be inferred that it originated from a source downstream of Danby. Similarly, in event 9 (31st March) the Grosmont SSC record is complicated by a second peak (discussed above), while this is not evident at Danby. Event 5 (27th March) is unusual because hysteresis is clockwise at Danby and anticlockwise at Grosmont. This shows that while at Danby near- or within-channel sources were most important in this event, at Grosmont sediment arriving later from more distant sources was of greater importance. This fits with other evidence to suggest that within-channel sources are more abundant and accumulate more readily at Danby than at Grosmont, whereas at Grosmont non-channel sources are more abundant and better connected with the river than at Danby because of the steeper valley sides.

The larger catchment area of Grosmont provides greater scope for the delayed arrival of sediment to the flow. Results from the time-integrated mass flux sampling (discussed in Chapter 4) show that tributaries entering the Esk above Danby all have low sediment yields. The three highest yielding tributaries, Butter Beck, Glaisdale Beck and Great Fryup Beck all enter the main Esk between Danby and Grosmont. Sediment sources above Danby are therefore likely to be predominantly from the channel banks of the main Esk, which are able to provide sediment quickly to the flow. Sources above Grosmont cover a wider area, being from both the main Esk and the tributaries, so travel times to Grosmont are more variable and are likely to result in a more complex hysteresis pattern.

5.4.2.3. Statistical analysis of hysteresis

Initial examination of the hysteresis direction in flow peaks (Figure 5.16) shows that clockwise hysteresis tends to favour events with high stage and SSC peaks. Anticlockwise and complex hysteresis generally occur in lower magnitude events. Clockwise hysteresis therefore occurs where sediment supplies are abundant. Nistor and Church (2005) also observed that SSC peaked earlier in first flow peak of a sequence, where sediment was more abundant, than in subsequent peaks, to which less sediment was available. Wood (1977) suggests that as sediment supplies become exhausted through a sequence of storms, hysteresis loops will become progressively wider. The data for the Esk appear to be more extreme than this because when supplies are exhausted the loop direction is reversed.

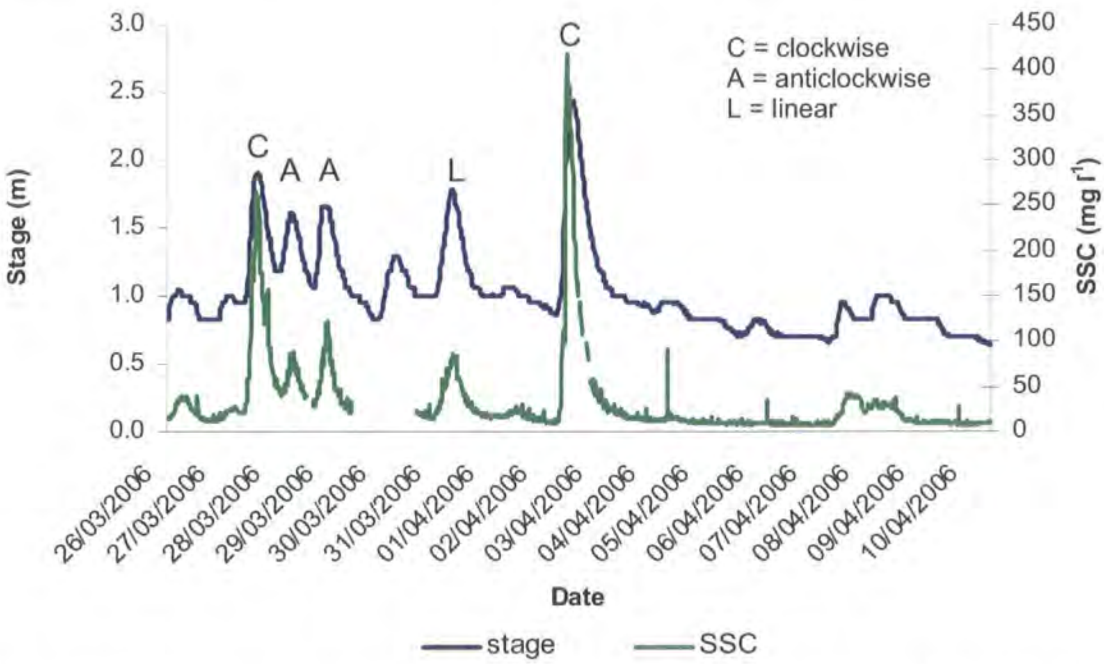

Figure 5.16. Danby storm sequence 4 showing the hysteresis direction for each of the analysed flow peaks.

In order to further examine the controls on hysteresis direction the storm characteristics for each event were investigated in relation to the hysteresis class. Attributes were chosen to characterise each storm, based on factors thought to be important in determining within-storm suspended sediment behaviour. The attributes used are:

- Event duration (time from initial rainfall to return to base flow)
- Peak stage
- Increase in stage (difference between initial stage and maximum stage)
- Lag time (time from initial rainfall to flow peak)

- Peak hourly rainfall intensity
- Total rainfall
- Rainfall total in previous 24 hours
- Rainfall total in previous 72 hours
- Number of days since a higher peak flow
- Peak SSC

The justification for selecting these variables is as follows: Events with a longer duration have a greater potential for sediment exhaustion. However, longer events also allow catchment wetness to reach to a higher level, which may increase connectivity between sediment sources and the channel. Peak stage and increase in stage both affect the number of sediment sources to which the flow will have access and be able to mobilise. Peak rainfall intensity may affect the extent of sediment erosion caused by surface runoff, while rainfall totals influence runoff volumes as well as catchment wetness and connectivity levels. Catchment wetness and connectivity are also likely to be dependent on rainfall totals in the days preceding the event. The number of days since a higher peak flow quantifies the potential for sediment accumulation preceding the event and, therefore, sediment availability to the flow. Peak SSC was chosen as a variable to show the maximum availability of sediment to the flow at any time during the event and the significance of the event in terms of suspended sediment transfer.

For the analysis at Grosmont the complex and anticlockwise events were grouped into one category as no difference could be detected between the attribute values for these two types of hysteresis. The linear event at Danby was omitted from the analysis due to the occurrence of only one event of this type. Within each hysteresis category the mean, minimum and maximum of each of the storm attributes were calculated. These are summarised in Table 5.2.

From the tables it can be seen that there are differences in the storm characteristics associated with each type of hysteresis. Although sample sizes are small, a t-test was used to identify attributes with statistically significant differences between the two classes (shown in bold). At Grosmont three attributes showed statistically significant differences (0.05 level) between the two hysteresis classes. These are i) peak rainfall intensity, which is higher for clockwise events, ii) total rainfall in the 24 hours preceding the event and iii) total rainfall in the 72 hours preceding the event, which are both lower for clockwise events. High rainfall intensity might lead to more surface runoff and sediment transport on the steeper slopes which border the channel in the lower reaches of the Esk. High antecedent precipitation and, hence, catchment wetness suggests that input from non-channel sources is a cause of anticlockwise hysteresis at Grosmont. This relates to the steeper valley slope and narrower floodplains above Grosmont and the probable higher density of field drains in Great Fryup and Glaisdale Becks, which allow greater connectivity during periods of high catchment wetness.

Table 5.2. (a) Characteristics of storm events analysed at Grosmont (n = 12).

	Clockwise (n=7)			**Anticlockwise/complex (n=5)**		
	Mean	max	min	Mean	max	min
duration (hrs)	49.50	97.25	26.50	39.15	63.00	18.75
peak stage (m)	1.15	2.29	0.72	0.96	1.32	0.72
stage increase (m)	0.66	1.57	0.24	0.40	0.84	0.09
peak hourly rainfall (mm h^{-1})	3.89	5.00	1.80	1.96	3.20	1.40
total rainfall (mm)	15.49	31.80	6.00	9.16	11.60	1.60
lag time (hrs)	16.11	29.00	5.75	16.25	36.75	9.00
peak SSC (mg l^{-1})	437.89	1063.88	108.42	231.71	499.67	108.1
24h rain total (mm)	1.06	3.40	0.00	4.16	6.20	1.20
72h rain total (mm)	7.14	15.20	0.40	13.48	19.40	5.80
days since higher peak	65.29	187.00	1.00	41.40	185.00	2.00

Table 5.2. (b) Characteristics of storm events analysed at Danby (n = 6).

	Clockwise (n=3)			**Anticlockwise (n=3)**		
	Mean	max	min	Mean	max	min
duration (hrs)	30.42	47.25	17.25	28.17	33.75	20.50
peak stage (m)	2.36	2.72	1.91	1.38	1.66	0.87
stage increase (m)	1.53	2.03	0.97	0.49	0.59	0.43
peak hourly rainfall (mm h^{-1})	3.40	5.20	1.80	2.00	2.80	0.60
total rainfall (mm)	10.80	14.40	6.80	6.87	8.80	5.20
lag time (hrs)	10.33	13.00	8.75	10.00	10.75	9.00
peak SSC (mg l^{-1})	445.44	556.20	332.40	93.36	130.68	55.00
24h rain total (mm)	4.00	7.60	0.80	3.00	6.80	0.00
72h rain total (mm)	12.33	14.20	10.60	13.53	16.00	9.80
days since higher peak	32.00	66.00	12.00	13.67	39.00	1.00

At Danby three attributes also show a significant difference (0.05 level) between the two types of hysteresis. These are peak stage, stage increase and peak SSC, which are all higher for clockwise than for anticlockwise events. This suggests the lower importance of non-channel sources at Danby, where the more extensive floodplain reduces the potential for non-channel sediment inputs. It also reflects the higher threshold for sediment mobilisation at Danby, where the channel slope is gentler and the grain size larger: in-channel sediment is only mobilised and exhausted in the large events, whereas at Grosmont the smaller grain size and steeper channel allow entrainment at lower peak stages.

For all of the attributes, except the three that are statistically significant at Danby, values between the two classes overlap. The trends described above are therefore only tendencies and not conditions needed for a certain type of hysteresis to occur. Hysteresis direction is probably dependent on a combination of attributes at certain levels, rather than on one influencing variable. The main overall trends that can be seen are that anticlockwise hysteresis is restricted to events of a lower magnitude, which transport lower concentrations of suspended sediment. This was also found to be the case by Olive and Rieger (1985) in a study of storm events in New South Wales. Clockwise hysteresis occurs in larger events where SSC, and hence sediment availability, are higher.

5.5. Temporal variation in mass flux suspended sediment yields

The analysis above has demonstrated that suspended sediment behaviour in the Esk is dominated by sediment exhaustion effects, both within and between storms, which is indicative of a supply limited sediment transfer system. The flow and turbidity data show variations at a high temporal resolution, but only at two points in the catchment. Mass flux samplers can be used to investigate temporal variations in sediment flux at different spatial scales. The sediment yields in the mass flux samplers represent time-averaged samples of the fluvial suspended sediment load during each of the seven sampling periods which ranged from 21 to 30 days in length. The mass of sediment collected is therefore a response to the flow and rainfall characteristics and catchment sediment production processes which occurred over the period. Temporal trends in the data will be explored first, followed by an analysis of mass flux yields in relation to flow characteristics

5.5.1. Temporal trends

To standardise for different lengths of sampling period, raw mass flux sediment yields were divided by the length of the sampling period to give a value of grams per day. The data show that yields at a given site have a high variability between sampling periods

(Figure 5.17). This indicates that temporal variation in suspended sediment loads in the river is high over an intra-annual timescale. Certain sites display greater variability than others. These include the tributaries of Butter Beck, Great Fryup Beck and Glaisdale Beck and the main Esk at Danby and Egton Bridge. The high number of outliers at the upper end of the scale show that many of the sites which generally have low yields are occasionally subject to periods of high yield. Examination of the data shows that all of the outliers are yields from the last sampling period (ending on 5th June 2006). This period resulted in the highest yields at all the sites, except for Great Fryup Beck, Westerdale Beck (where the sampler was lost during this period), Six Arch Bridge and Danby.

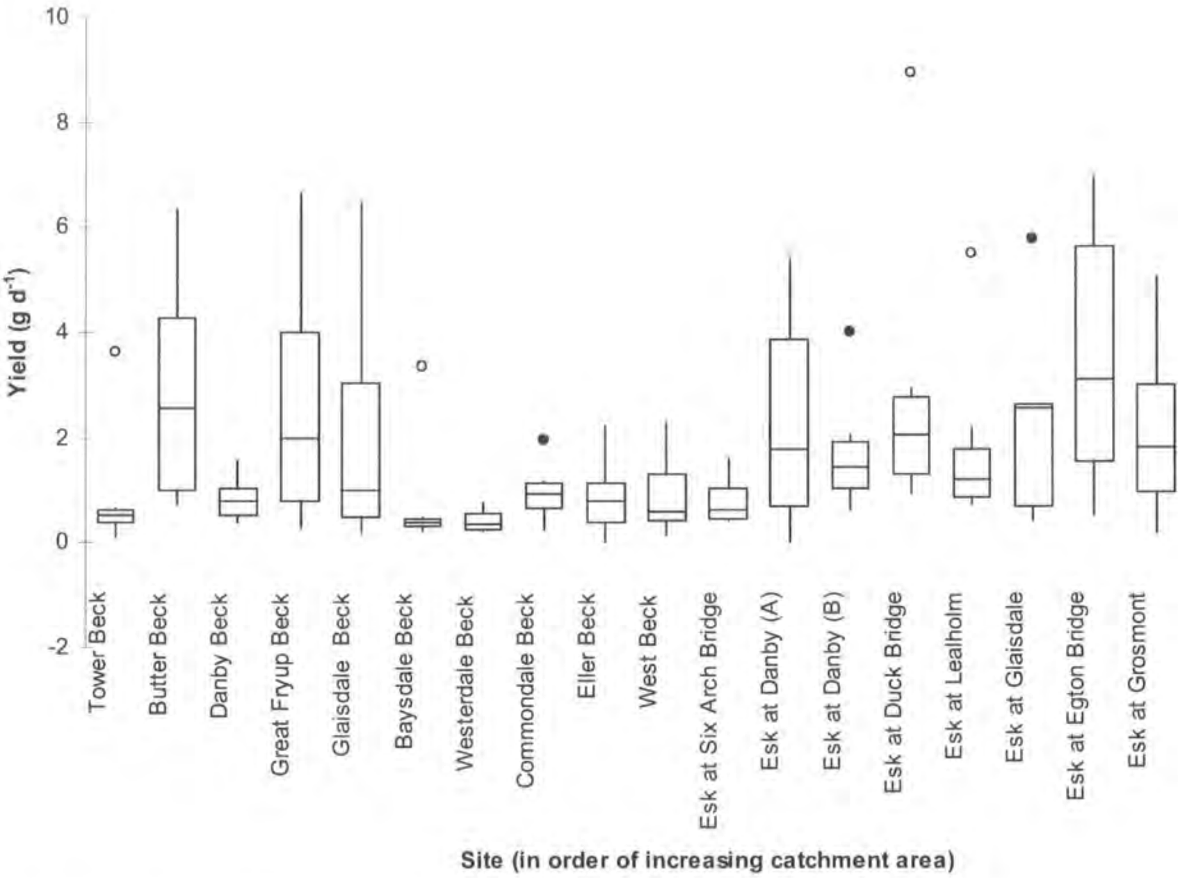

Figure 5.17. Mass flux sampler yields at each site between December 2005 and June 2006, standardised for differences in sampling period lengths (n = 7).

The reason for the high yields in the last period is the occurrence of an extreme high flow event on 22nd May, during which the stage at Danby reached 4.7 m, two metres higher than any other event during the monitoring period. This event was preceded by a flow which reached 2.7 m (Figure 5.18). The magnitudes of these two events allowed them to mobilise and transport large quantities of sediment. It is likely that the larger, second event was able to mobilise sediment which was unavailable to lesser events, for example by inducing bank failures, releasing fine sediment from beneath the channel bed armour layer or by allowing the connection of catchment sources due to extreme catchment wetness. It can be seen in Figure 5.18 that the two large events on 18th and 22nd May occurred after a long period of low flow. This may have enhanced the sediment availability by allowing stores of sediment to build up, such as through subaerial weathering of bare bank material, which could then be entrained during the high flow events.

The large range of yields shown in Figure 5.17 and the very high yields at extreme discharges are indicative of an episodic suspended sediment regime, where suspended sediment loads are dependent on the occurrence and magnitude of high flow events rather than simply on total discharge (e.g. Webb and Walling, 1984). This concept will be explored further in Section 5.5.2.

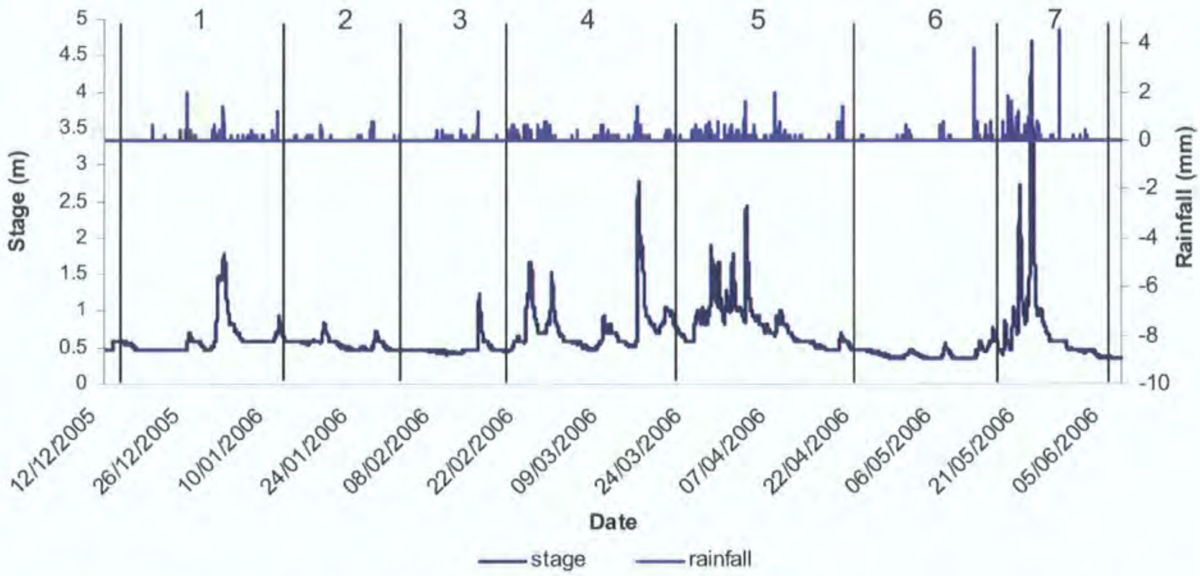

Figure 5.18. Flow and rainfall series at Danby showing each of the seven mass flux sampling periods.

Daily mass flux yields for each sampling period were averaged across all the sites and plotted on a bar chart (Figure 5.19). The data, being of less than a year, prevents detailed examination of seasonal trends, which might be expected if sediment production and transport were higher at certain times of year. When the mean sediment yields are compared to the flow in each period (Figure 5.18) it can be seen that the periods with the lowest mean sediment yields correspond to periods with no significant high flow events, while higher yields occurred where high flow events also occurred. Sediment yield, therefore, appears to be closely related to the discharge peaks.

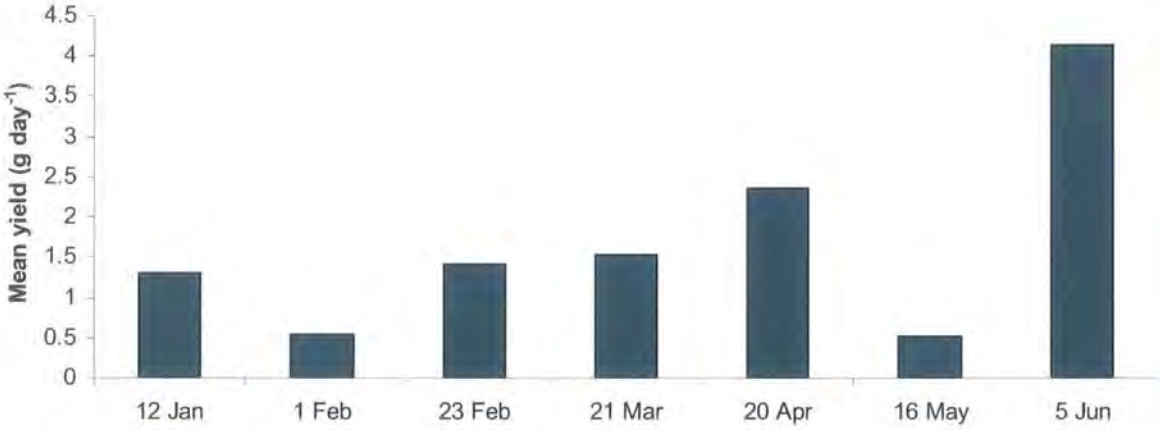

Figure 5.19. Mean mass flux sampler yield for each of the seven sampling periods, standardised to account for sampling periods of different lengths.

Yields from individual sites were expressed as a percentage of the mean yield for the sampling period. This allowed comparison of the relative contributions of yields from individual sites in different sampling periods (Figure 5.20). Missing values correspond to samples that could not be collected either due to high flow or because the sampler had been lost. The yield at Danby sampler A for 12 January was extremely high. When the sampler was recovered a clod of earth was found covering the entrance nozzle, which is thought to have caused higher rates of sediment flux into the sampler. The value was taken to be anomalous and was removed from the analysis. The graphs show that the distribution of yields between the samplers is not the same for each sampling period. However a similar general pattern can be seen for each period, with the proportionally high yields found in Butter Beck, Great Fryup Beck and Glaisdale Beck and sites on the main Esk and proportionally low yields found in other tributaries.

In Figure 5.20 it seems that in general during the sampling periods with lower mean yields, the total sediment flux is distributed more evenly between the sites than in sampling periods where mean yields were higher. In periods with higher mean yields some sites have much higher yields, relative to the mean than others; i.e. the increase in mean yield can be largely accounted for by disproportionately high increases in yield at a few sites. Comparison of the box plot in Figure 5.21 with Figure 5.18 shows the trend more clearly (with the last sampling period as an anomaly), although a longer sampling period is necessary to verify this.

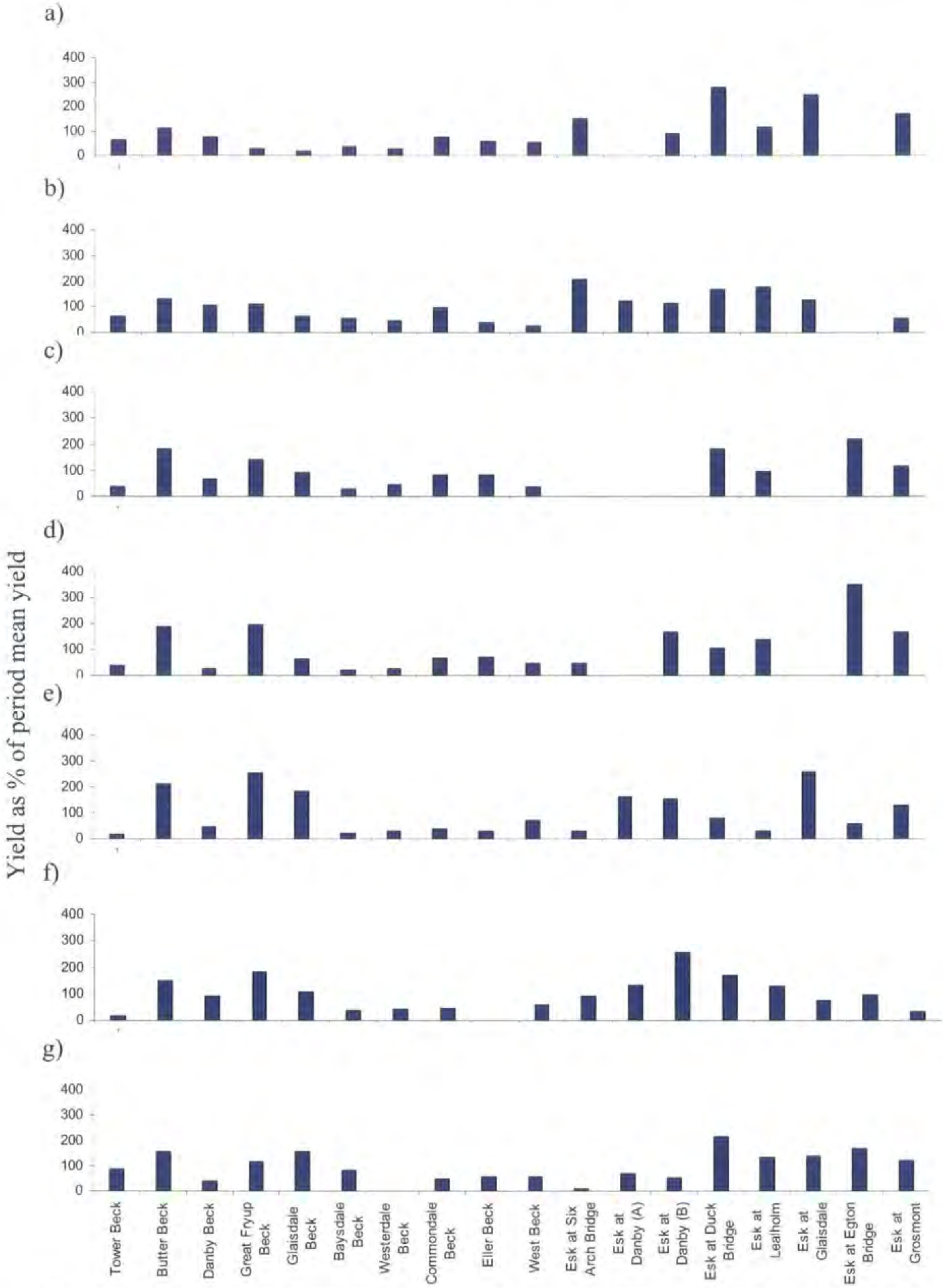

Figure 5.20. Mass flux sampler yields shown as a percentage of the period mean yield for each of the sampling periods: a) 14 December-12 January; b) 12 January-1 February; c) 1-23 February; d) 23 February-21 March; e) 21 March-20 April; f) 20 April-16 May; g) 16 May-5 June. Mean yield per day shown for each period.

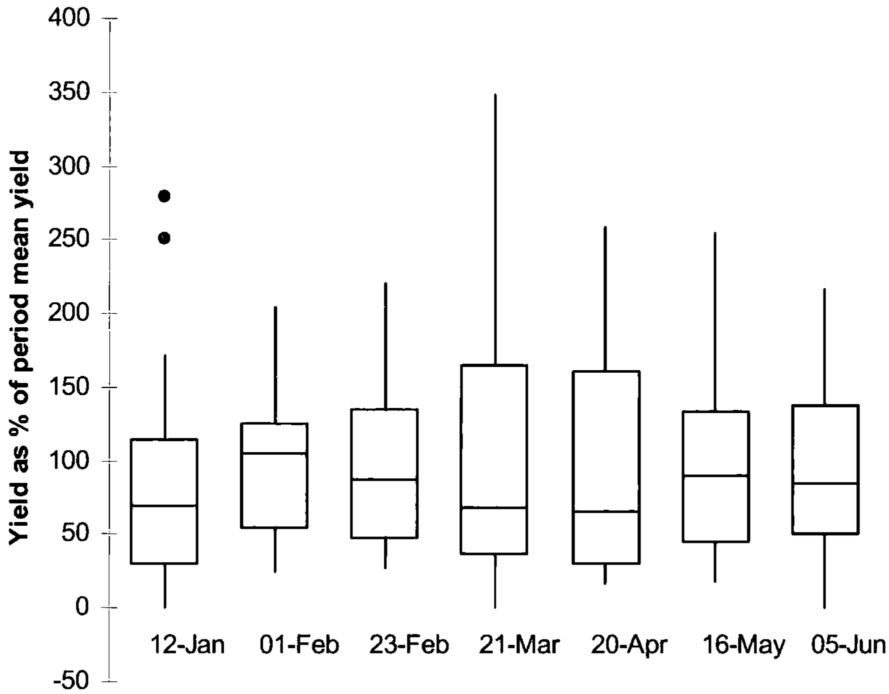

Figure 5.21. Range of mass flux yields as a percentage of the mean yield within each sampling period.

A suggested reason for the pattern is that in this supply-limited system few sediment sources are available to the flow at low discharges, so variation in yields between sites is lower. At higher discharges tributaries and reaches which have greater sediment availability, and therefore lower thresholds for sediment mobilisation, experience a greater increase in yield, compared to tributaries and reaches where sediment availability is lower and thresholds for sediment mobilisation and transport are higher. The one exception to this trend is the last sampling period where between-site variability in yields is low, but mean yield is by far the highest. This could signify that the extreme event of 22nd May was large enough to exceed thresholds for sediment mobilisation even in the channels where these thresholds are high. In the lower threshold, higher yielding channels the large event had a proportionally less extreme effect, possibly because of an exhaustion of sediment sources at a discharge this high.

The differences in response of channels to high flow events suggest that not all channels are dominated by the same sediment supply and transport mechanisms. This relates to the results of Chapter 4, where spatial variation in channel and riparian characteristics was observed. Differences in sediment transport thresholds might also be due to a non-uniform response of stage and discharge across the catchment during a high flow event.

For example, for a given increase in discharge, stage will increase more in a narrower channel. This may have an impact on the number of sediment sources which can be accessed by the flow. The flashiness of the responses of different tributaries to a storm may vary, depending on the nature of their catchment. Certain tributaries may therefore be more susceptible to sediment-mobilising flows. The response of the individual tributaries and reaches to different flow patterns will now be explored in more detail.

5.5.2. Hydro-meteorological influences on mass flux yields

The above analysis of temporal trends in the mass flux data highlights the importance of variations in discharge in determining yields. The analysis of within and between storm variations in SSC in Section 5.4 has shown that the relationship between SSC and discharge is not constant and is affected by sediment exhaustion effects. It has also been demonstrated in these sections that sediment transport is episodic and related to high discharge events. This sub-section will further explore the relationships between mass flux yields and a series of flow parameters. As the stage record at each mass flux sampling site is unknown, the stage record at Danby was selected for use in the analysis because it provides a continuous record for all seven sampling periods and it is a more detailed record than the one at Grosmont. It is also a more central site so its flow characteristics are likely to be more representative of the flows at a higher proportion of the other sampling sites. Four parameters were chosen to represent different discharge characteristics. These are shown in Table 5.3.

Table 5.3. Flow parameters selected for correlation analysis.

Parameter	Criteria
Mean stage	Mean stage over sampling period (m)
Peak stage	Peak stage during sampling period (m)
Number of flow peaks > 1 m	Number of times stage exceeded 1 m during sampling period (1 m chosen as an arbitrary value to represent a significant sediment mobilising event; at Danby flows exceeding 1 m occurred during approximately 10% of the sampling period)
Total rainfall	Total rainfall during sampling period (mm)

If the SSC is purely dependent on the discharge, we would expect to see a strong correlation between yield and mean stage. If the distribution of discharge within the sampling period is of greater importance than the total discharge we would expect to see a strong correlation between sediment yield and the parameters peak stage and number of flow peaks above a metre. Figure 5.5 has shown that SSC is not purely dependent on discharge. If sediment input from catchment runoff is important, the best correlations would be with total rainfall. In order to investigate these hypotheses the four parameters were entered into a correlation matrix with the mass flux yields as dependent variables (Table 5.4). The matrix shows that all the predictor variables are significantly correlated, except for peak stage and number of peaks above a metre. This is not unexpected, since they all relate to the discharge. However, this makes it more difficult to isolate the most important variables.

Table 5.4. Correlation matrix between mass flux sampler yields and flow parameters. Yellow cells show correlation significant at 95% level; orange cells show correlation significant at 99% level.

	Mean stage	Peak stage	No.peaks>1m	Total rainfall
Mean stage	1.00			
Peak stage	0.88	1.00		
No. peaks>1m	0.88	0.67	1.00	
Total rainfall	0.90	0.76	0.92	1.00
Tower Beck	0.63	0.91	0.36	0.45
Butter Beck	0.85	0.73	0.97	0.87
Danby Beck	0.57	0.60	0.67	0.53
Great Fryup Beck	0.75	0.53	0.96	0.83
Glaisdale Beck	0.75	0.72	0.85	0.73
Baysdale Beck	0.60	0.89	0.38	0.44
Westerdale Beck	0.67	0.64	0.90	0.71
Commondale Beck	0.84	0.91	0.70	0.73
Eller Beck	0.71	0.91	0.57	0.71
West Beck	0.84	0.76	0.92	0.85
Esk at Six Arch Bridge	-0.17	-0.34	-0.20	-0.23
Danby (mean)	0.60	0.34	0.89	0.72
Esk at Duck Bridge	0.61	0.88	0.38	0.46
Esk at Lealholm	0.67	0.93	0.36	0.53
Esk at Glaisdale	0.88	0.61	0.98	0.93
Esk at Egton Bridge	0.70	0.78	0.33	0.54
Esk at Grosmont	0.95	0.88	0.91	0.91

The matrix shows that certain variables are better related to mass flux yields than others. Mean discharge is correlated significantly with yields at five sites and only with two at the 99% level. If suspended sediment transport was purely dependent on discharge (i.e. transport limited) we would expect to see the best correlations between total discharge and yield. The fact that this is not the case suggests that, as hypothesised, factors other than discharge are more important in determining sediment transport. The correlation matrix shows that the yield from every site, except Danby Beck and Six Arch Bridge, is correlated either with the number of flow peaks above a metre or with peak stage and that most of these correlations are significant at the 99% level. Interestingly, only two sites, West Beck and Grosmont, are significantly correlated with both variables. Peak stage and the number of flow peaks above a metre are the variables which appear to explain the greatest amount of variation in yields and are, therefore, of greater importance than mean discharge.

The Danby flow record used in the analysis would be expected to be most closely correlated with the yields from the two samplers at Danby. Some variations in the yields from the two samplers exist and are attributed to local variations in SSC and blockage of the samplers by debris. The mean yield from the two samplers was used to represent the yield at Danby. The correlation matrix (Table 5.4) shows that yields at Danby are only significantly correlated with the number of peaks above a metre, but at the 99% level. This suggests that the distribution of discharge is important in determining sediment yields and is supported by the results from Section 5.4, where the episodic nature of sediment transport and the effects of sediment exhaustion on concentrations are demonstrated.

The other sampling sites which are correlated most strongly with the number of peaks above a metre include Butter Beck, Great Fryup Beck, Glaisdale Beck, Westerdale Beck and West Beck and the main Esk at Glaisdale. It has been suggested that in a supply-limited system a certain discharge will transport more sediment if it occurs over several flood peaks rather than during one flood peak because the overall sediment exhaustion effect is reduced by sediment production and replenishment between flow peaks (Smith and Olyphant, 1994). The good correlation between yields and number of flow peaks suggests this may be the case at these sites. The greater importance of flows above a metre than the peak discharge suggests that at these sites thresholds for sediment mobilisation might be lower, i.e. that more sediment is available to flows of a lower magnitude. Yields from the tributaries of Tower Beck, Baysdale Beck, Commondale Beck, Eller Beck, West Beck and the main Esk at Duck Bridge, Lealholm and Egton Bridge have a good correlation with the peak stage. This shows the importance of high flow events in transporting sediment in the reaches above these sites. As discussed in Section 5.5.1, higher magnitude events are more likely to exceed thresholds for sediment mobilisation and transport.

Total rainfall is significantly correlated with yields at five sites. Rainfall may cause some variation in yields, related to the sensitivity of catchment sediment sources to erosion and transport by runoff. However, some of the correlation between yields and rainfall can be accounted for by common relationships with flow parameters.

Table 5.4 also shows that correlations between flow parameters and sediment yields are stronger at some sampling sites than others. Danby Beck and the Esk at Six Arch Bridge are not significantly correlated with any of the variables. The low correlations show that factors other than flow are important in determining sediment yields at these sites. These might include sediment supply factors, or local sediment inputs which are unrelated to the flow regime, such as local bank failure, or input from a catchment runoff source. The Esk at Six Arch Bridge is particularly noticeable for having low, negative correlation coefficients for all variables, which suggests that the sediment transport mechanisms operating here differ from other sites. The two lowest yielding periods for the Esk at Six Arch Bridge were periods 4 and 7 (ending 21st March and 5th June), both of which included high flow events (Figure 5.18). This is surprising as the channel above Six Arch Bridge is characterised by extensive bank erosion, which would be expected to provide a readily available source of sediment at high flows. The sampler at Six Arch Bridge is situated in the middle of a wide, shallow channel with a coarse gravel bed. If the main source of sediment was the channel banks, lack of flow mixing might have resulted in unusually low SSC in the centre of the channel, whilst sediment was transported closer to the banks. An alternative reason for the unusual yields is that the sampler may have been blocked by debris on both these occasions, which prevented it trapping sediment.

Significant correlations at the 99% level between all the variables and yields at Grosmont, including a strong correlation between mean discharge and yield suggests that sediment transport is more closely related to discharge at this site. However, results from Section 5.4 show that sediment exhaustion and episodic input of sediment did occur at Grosmont. Further data collection is necessary in order to clarify the main influences on sediment yields at this site.

The dominant variable for each site was compared to the spatial analysis of catchment characteristics in Chapter 4. No obvious reason for the differences in the response to flow was apparent from the channel and catchment characteristics. Yields at sites with similar characteristics such as Danby and Duck Bridge, which are both on the upper floodplain and Glaisdale and Egton Bridge, which are both in the lower bedrock controlled section, respond differently to the flows. This shows that the factors which cause sediment delivery are complex and may be affected by characteristics which were unmapped or by differences in the flow regime at each of the sites.

5.5.3. Summary

This analysis has shown that the distribution of flow within the sampling period is of greater importance than the mean discharge in determining mass flux sediment yields. This supports the conclusions of Section 5.4 where sediment transport was found to be episodic and related to high discharge events, sediment exhaustion effects and episodic sediment inputs. The important variables, peak stage and number of peaks above a metre, suggest that the frequency and magnitude of high flow events are very important in determining rates of sediment flux. The differences between sampling sites in the response of sediment yield to these flow parameters also indicates that sediment supply and transport processes do not operate uniformly across the catchment.

6. Discussion and Synthesis

6.1. Introduction

The suspended sediment dynamics in the Esk are dependent on the spatial distribution of sediment sources and the way in which these sources respond to storm events (Chapters 4 and 5). This discussion aims to bring these two aspects of suspended sediment dynamics together in order to provide an explanation for the way the sediment system operates and consider this in the context of previous work on the Esk and other, similar catchments. The chapter will also discuss the implications of the results for the wider management issues in the Esk catchment.

This study has taken an integrated approach to the investigation of suspended sediment dynamics in the River Esk. The use of mass flux sampling increased the spatial resolution of fine sediment monitoring, showing sediment yields at 17 sites over time periods of three to four weeks. Sampling using turbidity monitoring and automatic sampling at two locations, allowed the dynamics of suspended sediment to be analysed at a high temporal resolution. The combination of these two approaches allows a comprehensive understanding of the overall suspended sediment dynamics of the river. In addition to the monitoring, catchment mapping allowed the trends identified in suspended sediment dynamics to be related to processes seen in the field. The combination of results enables identification of the areas of the catchment which supply the most sediment and also identification of the dominant sources and processes of sediment input (Figure 6.1). From a management perspective this is ideal as it allows efforts to be targeted towards the most vulnerable areas of the catchment and at the sources of sediment with the highest yields.

6.2. Sediment transport dynamics in the River Esk

6.2.1. Spatial variation in sediment yields

A distinguishing feature of the Esk is that there is a distinct change in sediment supply and transfer processes between the upper and lower parts of the catchment. This is shown by the dashed line across the centre of Figure 6.1. The division is highlighted by the mass flux yields, which showed that in the upper part of the catchment the main channel is the dominant source of sediment, whereas in the lower part of the catchment the tributaries are of greater importance than the main channel in supplying sediment. The different arrow widths on the right hand side of Figure 6.1 indicate the relative importance of sediment supplies from each area of the catchment in terms of specific sediment yield.

The suspended sediment dynamics in each part of the catchment are shown on the right hand side of Figure 6.1. Rapid delivery of sediment to the rising limb of floods and sediment exhaustion effects in both parts of the catchment indicate the importance of in-channel sediment sources. This was related to the results of catchment mapping to infer the dominant types of fine sediment input from each area of the catchment (shown on the left hand side of Figure 6.1). It can be seen that overall in the upper part of the catchment the main input is from channel bank slumping, poaching and in-channel sediment storage in the main Esk. In the lower part of the catchment the main overall input is from bank erosion, poaching, in-channel storage and land drainage in Great Fryup Beck, Glaisdale Beck and Butter Beck. Though sediment inputs from other types of source and other areas of the catchment do occur, they are less significant. The larger range of source types in the lower part of the catchment, including the possibility of non-channel input from land drains and steeper valley slopes, as well as local bank failure above Grosmont, results in a different hysteretic response at Grosmont than at Danby, where all sediment is derived locally.

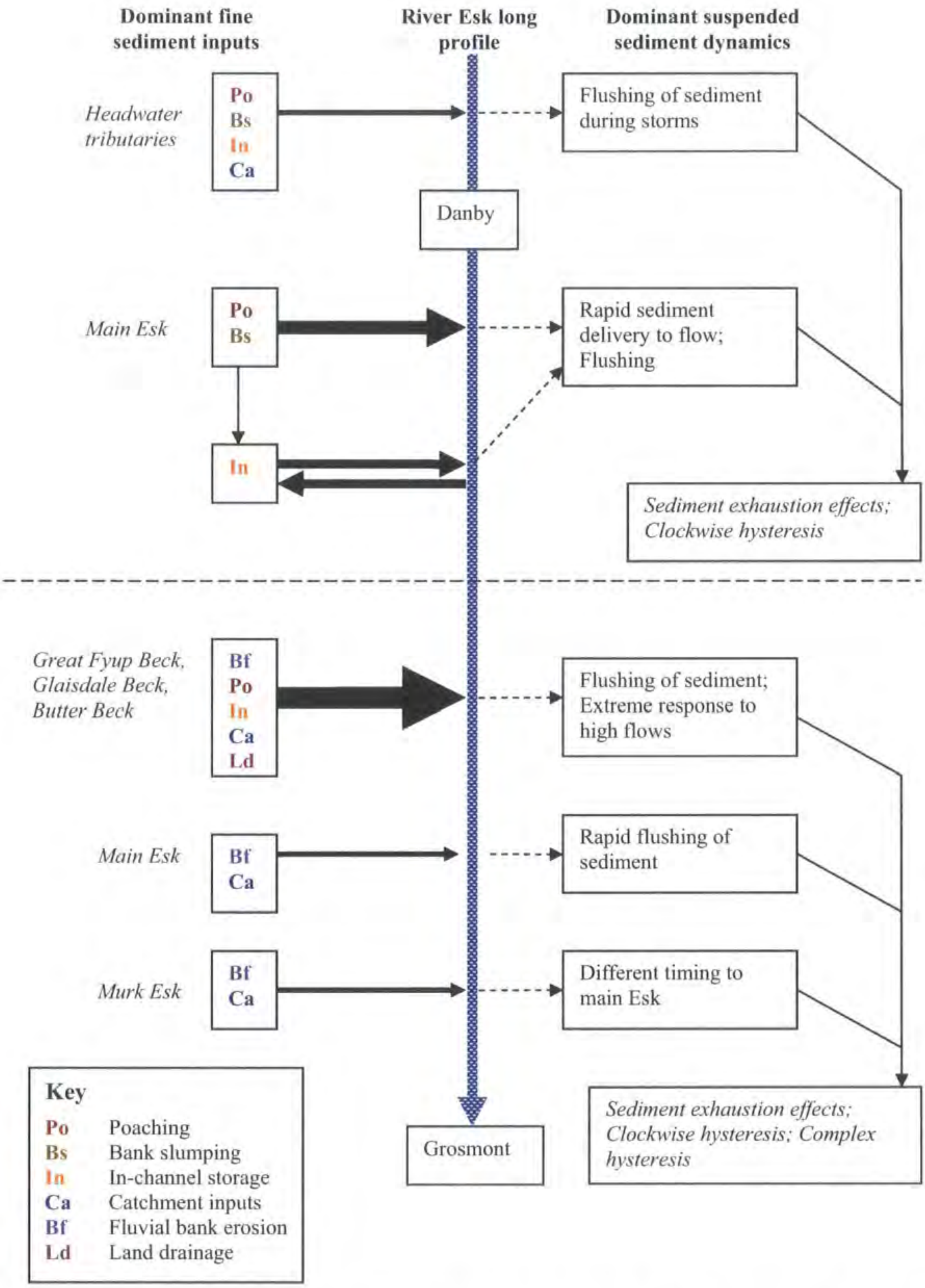

Figure 6.1. Conceptual model of spatial trends in fluvial fine sediment supply and transport processes

The consequence of the spatial variability in suspended sediment yields (shown by the input arrow width on Figure 6.1) is that the catchment conforms neither to the inverse relationship between specific suspended sediment yield and catchment area (Walling, 1983; Knighton, 1987), nor to the alternative model of increasing sediment yield with catchment area (Church and Slaymaker, 1989). The configuration of the geology and Quaternary drift deposits are the underlying cause of the spatial division in sediment sources and yields in the Esk catchment (Section 4.3.1). Land use and management processes are a secondary factor contributing to the variations in sediment yield. In the upper section of the catchment channel banks of alluvial sand on the main Esk yield large amounts of sediment. Livestock poaching was found to exacerbate this to a small degree. Headwater tributaries, despite having steeper valley sides, greater connectivity between sources and the channel, and the occurrence of poaching, have low rates of sediment production in comparison (Figure 4.9).

The Esk has a further complication because of the downstream change in channel and catchment characteristics. The easterly tributaries (Great Fryup Beck, Glaisdale Beck and Butter Beck) have high sediment yields which are thought to be a result of fluvial erosion of the boulder clay substrate. The more intensive farming practices in Great Fryup Dale and Glaisdale, including more extensive poaching and possibly a greater extent of land drainage, are another contributing factor. In Butter Beck human intervention is a dominant reason for the high yields (Section 4.3.2). The steeper boulder and bedrock dominated reaches of the main Esk further downstream do not supply large amounts of sediment because channel banks are stable against erosion, little sediment is stored in the channel and valley slopes are well vegetated. The trend between sediment yields and catchment area is therefore reversed in the downstream section of the catchment. The Murk Esk, comprising West and Eller Becks is another separate element in the system, which yields relatively low amounts of sediment because of its bedrock and boulder dominated morphology.

These results show the problems inherent in trying to conceptualise spatial variability in sediment yields as a simple function of catchment area (e.g. Dedkov, 2004). This approach does not readily take into account the processes behind the yield-catchment area relationship. The spatial variability in the geology and morphology of the Esk catchment demonstrates the complexity of these processes, and the importance of understanding them, in order to understand the functioning of the system as a whole. This is likely to be similar for many catchments, as demonstrated by other studies (e.g. Prestegaard, 1988; Church and Slaymaker, 1989; Bull *et al.,* 1995; Bathurst *et al.*, 2005). Knighton (1987: p 99) states that "such is the lack of data and intermittency of the transport process that sediment movement patterns at the basin scale are exceedingly difficult to predict". This study demonstrates the advantages of mass flux sampling as a simple way to increase knowledge of the spatial variability in yields in a catchment and avoid the need for unreliable predictions. In the Esk catchment the information on yields from the mass flux sampling has been integrated with temporal suspended sediment data to provide a spatial context for the analysis of within- and between-storm suspended sediment dynamics (Figure 6.1).

6.2.2. Temporal and spatial dynamics of fine sediment input

Clockwise hysteresis indicates that sediment is delivered rapidly to the rising limb of the flow and, therefore, that sediment originates from near to or within the channel (Klein, 1984; Jeje *et al.,* 1991; Jansson, 2002; Seeger *et al.*, 2004). Results from Chapter 4 show that bank erosion and slumping, poaching and in-channel sediment storage are dominant processes in the areas of the Esk which were identified in Section 4.2.2 as having the highest specific sediment yields (also shown by wide arrows in Figure 6.1). These in-channel sediment sources would therefore be expected to produce clockwise hysteresis. Section 5.4.2 showed that a clockwise pattern was the most common form of hysteresis, occurring in 9 out of 19 events; Table 5.2 shows that clockwise hysteresis tends to occur during events with the highest peak SSC values and the highest flow peaks. This supports the contention that within-channel sediment is indeed the main source of sediment to the Esk.

Many previous studies of hysteresis patterns have been carried out in drainage basins at least an order of magnitude smaller than the catchment area at Grosmont. It has been suggested that small catchment areas are more likely to exhibit clockwise hysteresis because sediment sources are closer to the channel (Collins, 1981; Labadz *et al.,* 1991). The dominance of clockwise hysteresis at both Danby and Grosmont shows that it is not confined to small catchments. The rapid response of SSC to rises in stage at both sites, despite large catchment areas, demonstrates the importance of sediment input from local channel sediment sources compared to non-channel sources from more distant parts of the catchment. In contrast to many other studies of hysteresis and suspended sediment transport (e.g. Klein, 1984; Brasington and Richards, 2000; Jansson, 2002; Nistor and Church, 2005), the importance of non-channel sources is relatively low in the Esk catchment because of the low intensity land use. The floodplain in the upper Esk reduces the connectivity between sediment sources and the channel, while steeper valley slopes in the lower reaches of the Esk are stabilised by trees, which prevent extensive mass-wasting.

In Section 5.4.2 it was discovered that there was a tendency for clockwise hysteresis to occur where overall SSC was high, often in the first storm in a sequence, while hysteresis direction was reversed later in a sequence of storms and where overall SSC was lower (Figure 5.16, Table 5.2). This implies that different sediment input processes tend to dominate when in-channel sediment supplies are lower, such as following sediment exhaustion. Anticlockwise hysteresis implies that most sediment arrives in the flow later in the event. In the Esk anticlockwise hysteresis is probably caused by the input of sediment from non-channel sources, which has a greater travel time to reach the river. At Grosmont the tendency for anticlockwise hysteresis to occur following high levels of antecedent precipitation supports this hypothesis: higher antecedent catchment wetness allows more sediment sources in the catchment to be connected to the river. This is a commonly reported cause of anticlockwise hysteresis in the literature (e.g. Jeje *et al.,* 1991; Seeger *et al.,* 2004; Armstrong, 2005). The lower peak SSC values in the events which display anticlockwise hysteresis, compared to those which display clockwise hysteresis, show that the overall amount of sediment supplied to the Esk by non-channel sources is less than that supplied from within-channel sources. The low intensity land use, large floodplain in the upper catchment and well vegetated slopes in the lower catchment are the reasons for the low yields from non-channel sources. The focus for understanding and managing fine sediment transfer in the Esk must therefore be on within-channel sediment sources.

The dominance of clockwise hysteresis suggests that episodic flushing of sediment through the system during storms is an important feature of the suspended sediment dynamics in the Esk (Figure 6.1). Section 5.5 showed that rates of suspended sediment mass flux are sensitive to the magnitude and frequency of flow peaks. This demonstrates that many major sediment inputs to the Esk have high thresholds for mobilisation and are only mobilised by the most extreme flows. High magnitude events are more likely to have the capacity to induce large scale bank failure and to remove debris blockages, causing sudden, large sediment inputs, as demonstrated by extensive deposits of both gravel and fine sediment at the mouth of Glaisdale Beck following the large storm on 22 May (Figure 6.2). The magnitude and frequency of high flow events is therefore an important factor determining overall rates of suspended sediment transport in the River Esk. Changes in the rainfall patterns in Northern England, due to climate change (Osborn and Hulme, 2002), may alter the flow regime of the Esk and, hence, the frequency of flow events with the capacity to mobilise certain sediment supplies (e.g. Longfield and Macklin (1999).

Figure 6.2. Sediment deposits at the mouth of Glaisdale Beck following the large event on 22nd May (note trash in tree).

Analysis of the temporal dynamics of suspended sediment transport provides information about the rate and timing of sediment supply to the flow and hence allows more detailed understanding of the dynamics of sediment input. Clockwise hysteresis indicates high initial sediment availability in the channel. Analysis of between-storm SSC variations showed that flow peaks preceded by a longer period of lower flow tend to have a higher SSC relative to the size of the flow peak because sediment supplies are less exhausted (Section 5.4.1). This was also found to be the case by Wood (1977) and Armstrong (2005). On the Esk, however, variability in this trend shows that sediment recharge is not temporally constant. Figure 5.7 demonstrates that it is possible for sediment availability to increase significantly in a short time period between two events, while episodic input of sediment during a single storm event was also observed, probably related to bank failure (Figure 5.14).

The dynamic of the main sediment supply processes to the channel is therefore episodic, which relates to the process of channel bank slumping, an important sediment input process in the upper main Esk and some tributaries. It is hypothesised that the process of channel bank slumping on the upper main Esk is comparable to that described by Ashbridge (1995) for the River Culm (Figure 6.3). Banks are characterised by a period of episodic slumping, induced by basal fluvial erosion. Slumped blocks of material then protect the toe of the bank from further erosion, allowing a period of stability until they have been entrained. The reworking of slumped bank material is a significant within-channel sediment source in the Esk and a primary contribution to clockwise hysteresis. However, the bank slumping process operates over a longer timescale than the within storm timescale at which sediment exhaustion effects were evident. Smaller scale but higher frequency processes which occur on top of the main cycle of bank slumping, such as subaerial weathering of exposed bank material and weathering of slumped blocks in the channel, result in a supply of loose sediment readily available for entrainment by the next high flow.

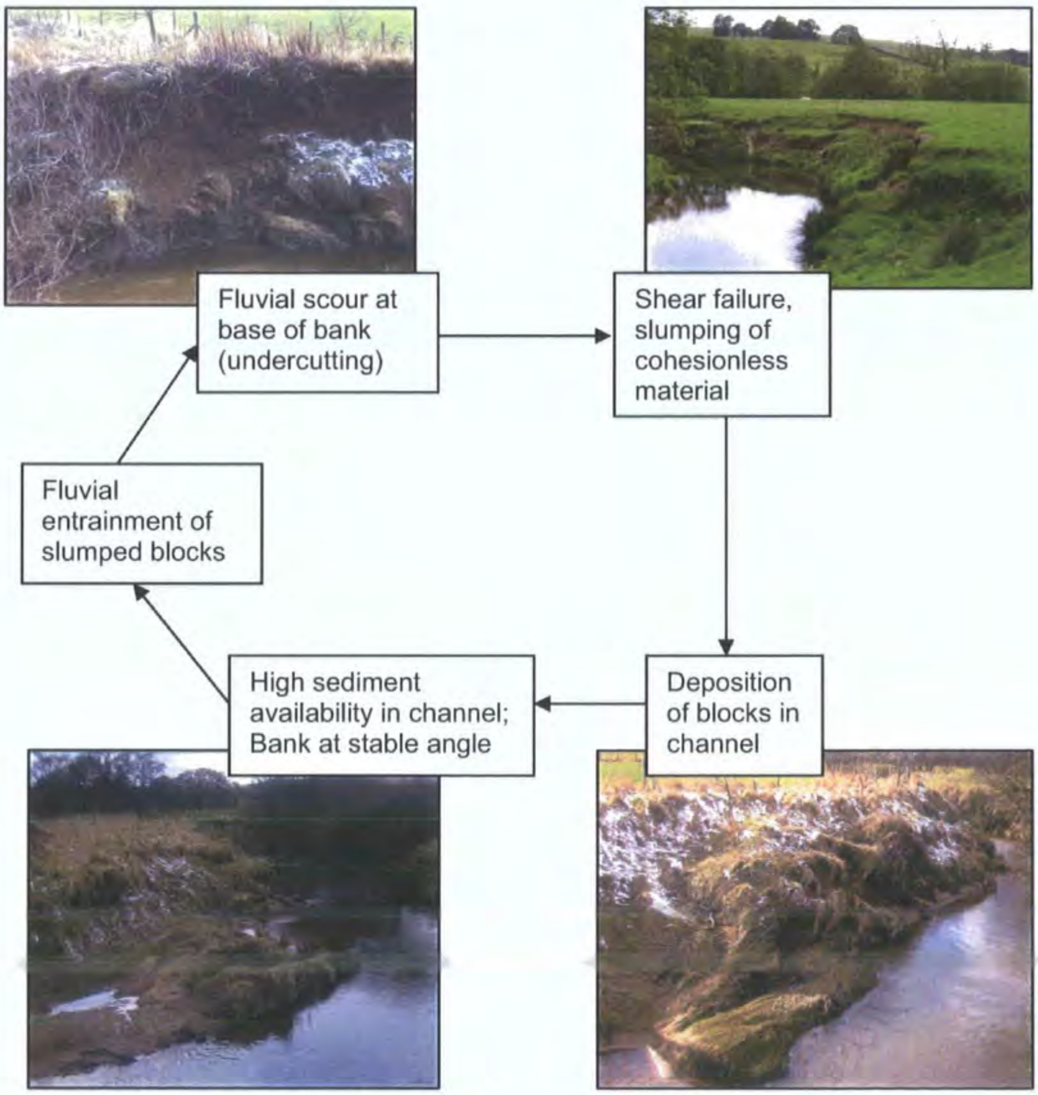

Figure 6.3. Suggested cycle of channel bank slumping on the River Esk.

A second important source of sediment is from within-channel storage in the form of point and side bars in meandering reaches, or in pools (Figure 6.1). Stored sediment may include slumped bank material; in addition, the retention of sediment in the channel by debris blockages is a common and significant form of in-channel sediment storage, particularly in the tributaries. Sediment recharge and exhaustion processes of stored material probably operate in a similar way to bank erosion processes, in that they consist of small scale sediment accumulation processes and high-magnitude, low-frequency inputs from the breaching of debris jams, and hence add to the episodic nature of inputs. Little work has been done to quantify the amount of sediment (particularly fine sediment) trapped in small channels by large woody debris, and the effect of this on the suspended load of rivers. The large amount of sediment released from storage following clearance of debris in Butter Beck demonstrates the high potential for this form of sediment storage and hence the need for further study.

Analysis of within- and between-storm suspended sediment dynamics has shown that, despite the differences in sediment sources above Danby and Grosmont, suspended sediment dynamics are largely similar at the two sites. This is because within-channel sources are the dominant type of supply in both parts of the catchment. The reach directly above Grosmont is characterised by high channel banks so local bank failure events supply sediment to the channel at Grosmont as well as at Danby. Close examination of the suspended sediment dynamics, however, shows that some differences between the two sites do exist.

At Grosmont the larger catchment area, greater input from tributaries and lower input from in-channel sources on the main Esk results in a more complicated temporal pattern of suspended sediment transport. This is reflected in the occurrence of some complex hysteresis patterns at Grosmont (although simple clockwise hysteresis dominates) (Section 5.4.2) Jeje *et al.* (1991) suggested that complex hysteresis occurs during longer duration storms which have the potential to mobilise and connect sediment from many different parts of the catchment. This was not found to be the case at Grosmont, where complex hysteresis tended to occur during the lower magnitude events. These events also had lower overall SSC values, suggesting input from channel sources was less dominant and input from other parts of the catchment of greater overall importance, thus causing complex hysteresis patterns. At Danby simple hysteresis patterns show sediment inputs are less complex, reflecting the greater dominance of local within channel sources. At Danby, hysteresis direction was found to be sensitive to the height of the flow peak. This reflects the larger grain size of the sediment found in the banks at Danby, which requires a higher threshold of flow for mobilisation, compared to the finer sediment found at Grosmont. At Grosmont the higher sensitivity of hysteresis direction to antecedent precipitation relates to the higher connectivity of the catchment above Grosmont. This is due to steep valley sides along the main Esk, Murk Esk and some of the tributaries. Field drains in the valleys of Great Fryup and Glaisdale Becks may also increase connectivity in this part of the catchment.

Smith *et al.* (2003) found that sediment loads from the different tributaries in the Swale catchment depended on the nature of the storm event, which implied that the varying sediment sources in different parts of the catchment responded differently to the different conditions in each of the storms. In the Esk the analysis of mass flux data in relation to flow and rainfall characteristics (Section 5.5) showed some spatial variability, but interpretation was difficult due to the occurrence of several storms in a study period. Mass flux sampling does have potential for quantifying spatial variability in relationships between flow and suspended sediment yields, but samplers would need to be emptied after every storm event.

6.3. Historical legacy on fluvial fine sediment dynamics

The discussion above has shown the complexity of the fluvial fine sediment transport regime in the Esk. From this process-based perspective, the concept of system memory emerges as an overarching theme. This concept was highlighted in Chapter 2 as being of significance in the understanding of fluvial fine sediment dynamics. The importance of variation in sediment supply and fluvial processes over time can be seen at a variety of scales in the Esk catchment (Figure 6.4).

Sections 4.3 and 6.2 have shown that the dominant sediment sources and the contemporary rates and mechanisms of sediment supply in the Esk catchment are strongly influenced by the geology and, in particular, the Quaternary deposits in the catchment. The occurrence of lacustrine sediments in the upper Esk valley and boulder clays in much of the lower catchment and tributary valleys is a result of Devensian glacial and paraglacial processes (Figure 6.4). Processes which occurred in the catchment over 10,000 years ago therefore have a continuing influence over the operation of contemporary fluvial sediment transport processes.

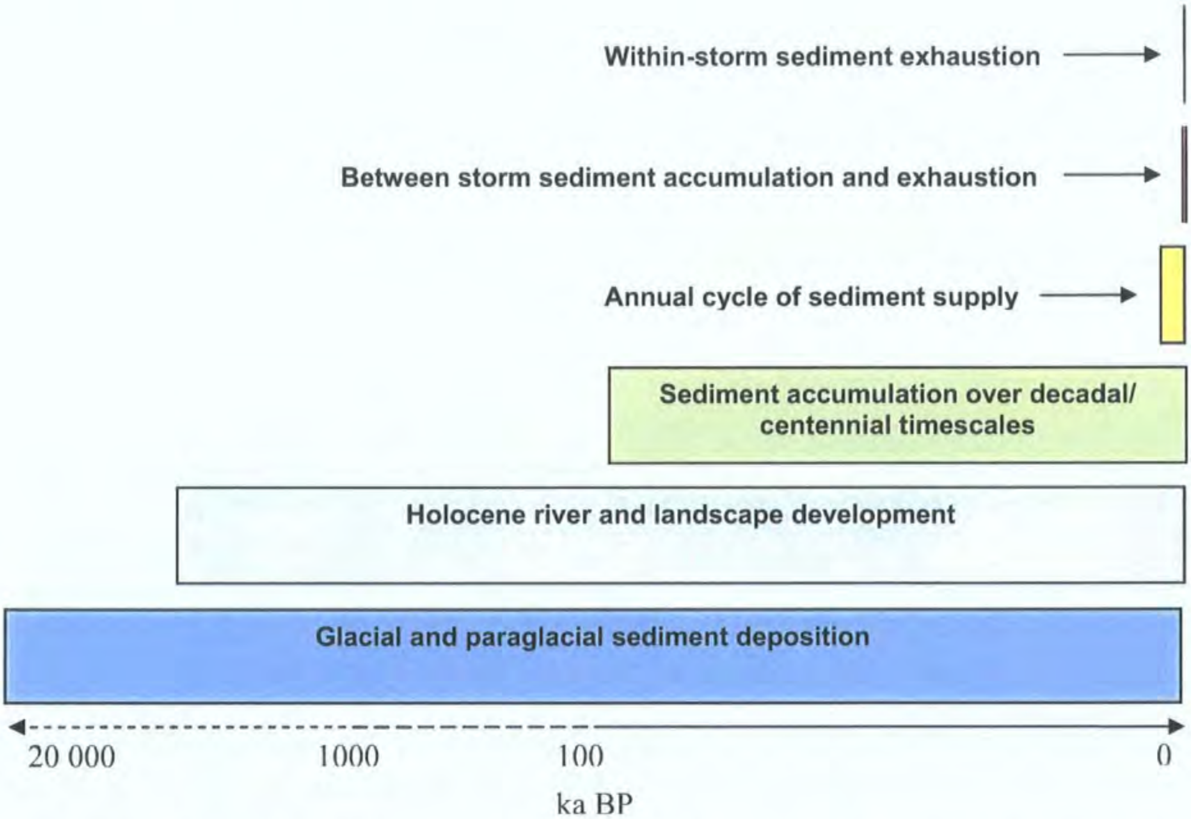

Figure 6.4. Timescales at which the historical legacy within the system operates to influence suspended sediment flux.

Over a shorter timescale the meanders and incised nature of the upper Esk represent the response of the river to its dominant process over the Holocene: reworking of alluvial and lacustrine deposits. The steps in the long profile (Figure 4.27) show that the river is still adjusting to its current catchment configuration. Channel incision, especially into the unconsolidated sands and gravels of the upper Esk floodplain, is the response of the river to an increase in gradient following glacial deposition. To assess lateral channel change in the historic past the plan-form of the main Esk on a current Ordnance Survey map was compared to a map of the Esk from 1853 and reaches of change were identified (Figure 6.5). The diagram shows that the plan-form of the upper Esk has remained broadly similar over the last 150 years; significant channel change has only occurred on some meander bends. Despite the dominance of slumping, the Esk is currently relatively laterally stable. The current form of the Esk may therefore be a relict from past processes, which formed the meanders when lateral migration was more active. In the lower part of the catchment glacial drift deposits caused the diversion of streams and resulted in the development of gorges, such as at Glaisdale and in parts of the Murk Esk (Eyre and Palmer, 1973). This has influenced the channel bank material and the valley morphology, which in turn influences current sediment availability and connectivity.

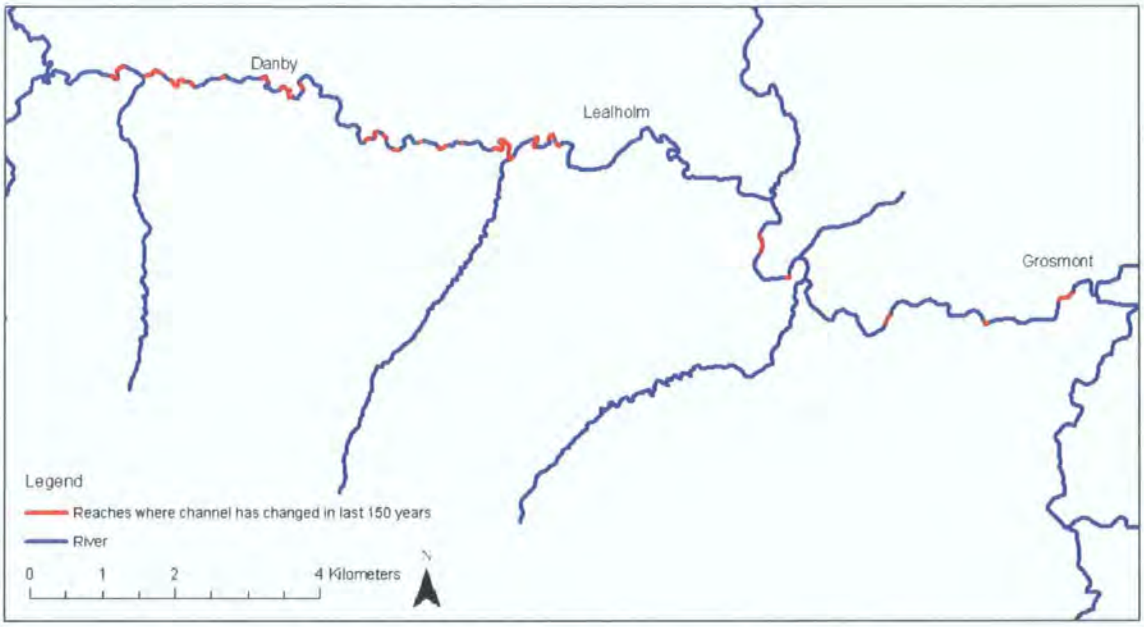

Figure 6.5. Plan form change on the main Esk between 1853 and 2005.

Figure 6.4 also highlights the importance of the legacy of past processes on contemporary suspended sediment dynamics at small timescales. SSC during a high flow event is a response to the sediment availability, which is itself dependent on the operation of sediment supply processes preceding the event and the extent of sediment exhaustion by previous events and thus incorporates an element of system memory. This is demonstrated by the suspended sediment dynamics of Butter Beck (Section 4.3.2). The high suspended sediment yields in this tributary are a response to the clearing of large woody debris from the channel five years ago which released large volumes of sediment from storage and vastly increased sediment availability. Increased sediment loads represent the continuing adjustment of the channel to past perturbation, in an attempt to regain an equilibrium state.

In other channels sediment availability varies over smaller timescales. It is likely that sediment availability fluctuates seasonally, in response to the different rates of sediment supply through processes such as desiccation and freeze-thaw but the timescale of the study prevents the testing of this hypothesis. The effect of system memory is, however, evident at a between-storm scale. Sections 5.4 and 6.2 showed the importance of the sediment exhaustion effect on sediment availability, whereby higher SSCs often occurred in storms which were preceded by a longer period of low flow. The input of sediment from channel bank slumping incorporates an element of system memory (see Figure 6.3). A previous event might have triggered a bank collapse, but this would typically occur on the falling limb (Rinaldi *et al.*, 2004). Sediment supply to the next flow peak would therefore be higher as a result of the processes which occurred prior to the event. This section has shown that the operation of sediment transport processes at every timescale must be seen as a response to past as well as present conditions. The incorporation of sediment supply factors into rating equations represents an attempt to quantify the effects of sediment supply and depletion on sediment transport rates. Measures of catchment antecedent conditions are used to predict the sediment supply factor (e.g. Van Sickle and Beschta, 1983; Moore, 1984; Picouet *et al.,* 2001).

6.4. Management context and implications

The results of this study build on those of Babtie Brown & Root and The Environment Agency (2004). Babtie Brown & Root and The Environment Agency (2004) aimed to identify the channel and riparian character of the Esk and its tributaries, and from this to infer the dominant areas of the catchment supplying sediment and the dominant processes responsible. The distribution of sediment sources and sinks was used to suggest patterns of sediment transport in the Esk. Although the study was able to identify the areas of the channel where the potential for sediment supply was high, actual rates of sediment transport from each area of the catchment were not measured. This limited the specificity of the management suggestions that arose from the work. Babtie Brown & Root and The Environment Agency (2004) established that fine sediment supply from point sources was highest in the tributaries of the Esk, excluding Baysdale, Commondale and Tower Beck, while diffuse sediment sources (i.e. bank erosion) were highest in many parts of the Esk and its tributaries above Glaisdale. Storage of sediment in the channel was found to be high in the main Esk upstream of Glaisdale, and in several tributary reaches. Although the channel mapping reported in this study found similar channel characteristics as Babtie Brown and Root and Environment Agency (2004), the addition of fine sediment monitoring allowed far greater inferences to be made about the sediment supply and transfer processes in the

Esk. It was shown that, despite high potential for sediment supply in many tributaries, actual transport is highest in Butter Beck and Glaisdale Beck.

Babtie Brown & Root and The Environment Agency (2004) concluded with the recommendation that the reduction of the supply of fine sediment to the channel is the best way to reduce fine sediment transport, and that this should be done by management of the riparian zone. However, they were unable to be more specific because mapping could identify neither the dominant processes of sediment supply, nor the dominant areas of the catchment for sediment supply. Although the results of this study broadly agree with their recommendation, they have far greater value from a management perspective because the combination of mapping and monitoring allowed identification of the areas of the catchment in which the management should be focussed and the dominant sources of sediment which should be targeted within these areas. These areas are identified on Figure 6.6 as being the main Esk channel above Lealholm and the tributaries of Glaisdale and Butter Becks.

Input from channel banks is the main source of sediment in the upper Esk. Particularly eroding reaches are found on the main Esk from slightly upstream of the confluence with Commondale Beck to the confluence of Danby Beck, between Danby Moors Centre and Duck Bridge and for about 1.5 km downstream from the confluence of Great Fryup Beck (Figure 4.17). Bank erosion is also a dominant sediment source in the tributaries (except for the Murk Esk), especially parts of Great Fryup Beck, Danby Beck, Westerdale Beck and Tower Beck (Figure 4.17). However, the lower bank heights in these tributaries reduce the overall amount of sediment produced from bank erosion. Since Great Fryup Beck has the highest sediment yields of these tributaries, this should be the tributary where reduction in bank erosion is a priority, followed by Danby Beck, where bank erosion is more widespread and sediment yields are higher than other headwater tributaries (Figure 6.6; Table 6.1). Much of the input from bank erosion, however, is natural and occurs as part of the process of scour and slumping on the outside of meander bends, the formation of point bars on the inside of bends and reworking of slumped and deposited material. A study of historic channel characteristics would show whether the Esk is wider or more incised now than in the past and hence whether the current rate of erosion of the Esk is elevated.

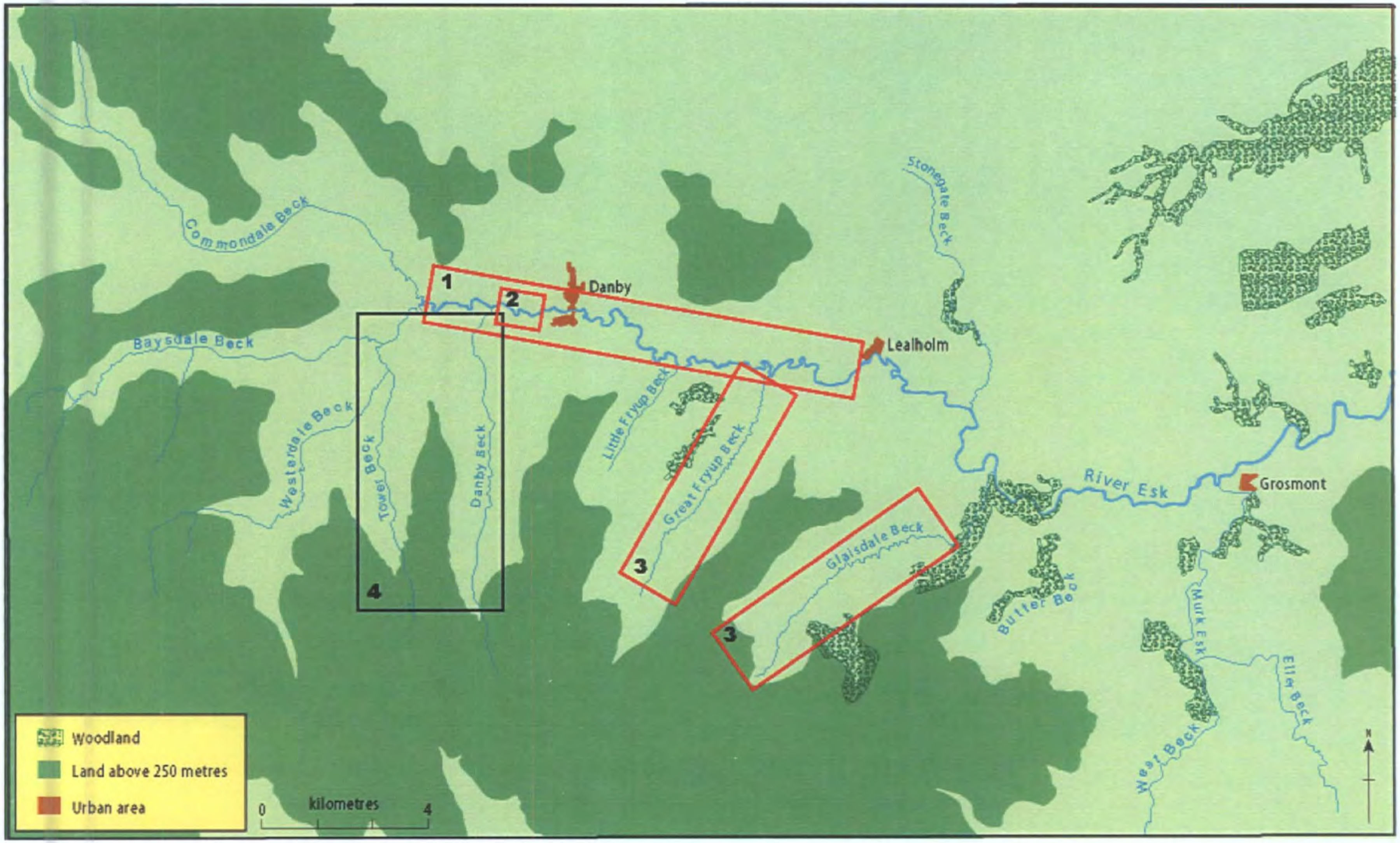

Figure 6.6. Areas of management priority for the River Esk, corresponding to Table 6.1 (areas in red boxes are of higher priority).

Table 6.1. Suggested fine sediment management strategies for the upper Esk catchment.

Box on Fig. 6.6	Area	Priority level	Suggested works
1	Main Esk above Lealholm	High	Vegetate bare banks
2	Main Esk below Six Arch Bridge	High	Fence channel to alleviate poaching
3	Great Fryup Beck, Glaisdale Beck	High	Vegetate channel banks Fence channel to alleviate poaching Use of willow and brushwood to stabilise banks of extreme instability Research extent of land drains
4	Tower Beck, Danby Beck	Medium	Vegetate channel banks (Danby Beck) Fence channel to alleviate poaching

Management of eroding reaches should focus on reducing sediment supply from the banks. Personal communication with Andrew Delaney of the Environment Agency revealed that in the past, in some reaches of the main channel the banks were vegetated with heather. Along the main Esk a cover of grass and other herbaceous vegetation would not necessarily prevent slumping because its rooting depth is shallower than the depth at which the banks fail. However, a more extensive vegetation cover would reduce the amount of exposed sediment on the channel bank, thus reducing the availability of sediment to the flow. Blocks of slumped bank material in the channel are more likely to resist entrainment by flow if they are well vegetated (Ashworth, 1995), which would reduce the rate of sediment supply and also protect the bank toe from fluvial erosion, thus reducing the rate of slumping. The benefit of trees in stabilising banks is somewhat reduced by trees which cause bank failure, due to their loading. Trees which have fallen into the river also cause retention of fine sediment in the channel and the flow obstruction may also cause bank scour. However, on the whole, banks were more stable in reaches with established trees. In reaches where slumping is active, this is unlikely to allow trees to become established on channel banks. However, the planting of trees on banks which are currently stable will be beneficial in the long term. If bank slumping does occur as a cycle, as suggested in Section 6.2, the binding of the bank sediments provided by the trees may help prevent the relapse of a stable bank to a slumping one.

In the tributaries eroding banks were generally lower and steeper than on the main Esk and are likely to be more difficult to vegetate. Simple bank stabilisation measures involving willow stakes, observed in the upper reaches of Commondale Beck and in small areas of other tributaries (Figure 4.24), were successful in reducing sediment supply from an area of extreme bank instability. These could be applied to other tributary reaches experiencing severe bank erosion, but should not be used too extensively as this would cause sediment starvation and prevent the operation of natural processes.

Livestock poaching was observed on one area of the main Esk, downstream of Six Arch Bridge (Figure 4.22). This could be managed by fencing the area. Poaching was more commonly observed on tributaries than the main Esk because lower channel banks allow livestock greater access to the river. Many reaches of tributary were well fenced; poaching occurred in only a few locations in most tributaries. Management should focus on improving fencing and reducing livestock access to the channel in these locations. Attention should be paid particularly to Great Fryup Beck and also to Glaisdale, Danby and Tower Becks (Figure 6.6; Table 6.1).

In the reaches and tributaries identified as having high specific sediment yields, mobilisation of sediment from in-channel storage is a source of sediment during high flows. In the main channel of the Esk above Lealholm sediment storage on the channel bed results from high rates of sediment input from the channel banks, and because of the larger grain size and lower competence of the flow in these reaches. Some sediment storage behind woody debris was also observed. In tributaries debris blockages were more common and sediment storage in the form of point and side bars was also common. As demonstrated in Butter Beck, removal of all large woody debris is likely to disturb the system and result in increased sediment supply for a period of time. Debris and storage of sediment in channels is important in order to create a variety of habitats (Gregory, 1992). Management of fine sediment in the tributaries should therefore focus on reducing the initial input of sediment to the system, as outlined above. The high sediment yields from Butter Beck are human-induced and are likely to be reduced when the system regains equilibrium.

The high sediment yields from Glaisdale, Great Fryup and Butter Becks are probably partly related to the underlying substrate of these tributaries; they may have naturally higher yields. The extent of tile drainage in the valleys of Great Fryup and Glaisdale Becks is unknown, but thought to be high. An investigation into the extent of tile drainage in their catchments may also show this to be an important sediment source. If so, management strategies to reduce the input of sediment from drains should be undertaken.

Strategies to manage the fine sediment in the Esk should appreciate that a certain level of fine sediment is natural and inevitable, given the nature of the substrates in the catchment. Fine sediment is also desirable in terms of habitat variability for species such as lamprey (Maitland, 2003; Owens *et al.,* 2005). Without past data for the Esk the 'natural' level of fine sediment in the river is difficult to determine. Management should therefore aim to reduce sediment availability in areas of obviously elevated sediment production (e.g. areas of poaching and high bank instability), but to preserve the natural operation of the system. The discussion of the importance of system memory in Section 6.3 shows that management practices are likely to have long-term impacts on the functioning of the system. This highlights the need to consider the implications of management policies on future, as well as current, fine sediment behaviour.

7. Conclusions

7.1. Summary of findings

The aim of the study was to relate spatial and temporal trends in fine sediment flux during storms to catchment and storm characteristics, in order to understand how sediment production processes and transfer mechanisms operate in the upper Esk catchment.

The first objective was to quantify the spatial variation in sediment yields within the Esk catchment. The project used mass flux sampling to understand spatial variability in sediment yields in a catchment where this is complex. Specific sediment yields in the Esk show a poor relationship with catchment area. The catchment can be divided broadly into two sections. In the upper part of the catchment the highest sediment yields are from the main Esk channel, whereas in the lower part the highest yields are from the tributaries of Great Fryup Beck, Glaisdale Beck and Butter Beck. The highest discharge-weighted specific mass flux sediment yields are from Butter Beck and Glaisdale Beck; the lowest are from Baysdale Beck and Commondale Beck. The primary influences over spatial variability in suspended sediment transport are the geology and glacial deposits in the catchment. These affect, firstly, the erodibility of the substrate and, secondly, the channel and catchment morphology which in turn affects sediment transfer rates and processes. Land use is a second factor affecting sediment yields, primarily through the influence of livestock poaching on channel banks but also due to grazing pressure on pasture and possibly due to land drainage (the extent of which requires further research). Extremely high yields in Butter Beck are due to the release of stored in-channel sediment when woody debris was removed from the channel in a management effort.

The second objective was to determine whether suspended sediment concentrations during storms are related to the supply of sediment available for transport. The poor relationship between suspended sediment concentration and stage implies that suspended sediment transport is supply limited. Over the timescale studied, the major control over temporal variability in sediment availability was sediment exhaustion effects. Clockwise hysteresis, indicative of sediment exhaustion during an event, occurred in 9 out of 19 events analysed. Sediment exhaustion between storms was also observed in some cases, but the fact that peak suspended sediment concentrations were sometimes seen to increase within an event or a series of events showed that the rate of sediment accumulation is not temporally constant and is characterised by episodic inputs of sediment.

The third objective was to infer the dominant processes of fine sediment input during floods by investigating between- and within-storm suspended sediment dynamics. Mass flux yields showed stronger relationships with the number of flow peaks above a threshold and the highest flow peak during the sampling period than with mean stage. This sensitivity to high flows indicates that flushing of sediment through the system is a predominant mechanism of sediment transfer. Clockwise hysteresis tended to occur in events with the highest suspended sediment concentrations and highest peak stages. From this it was inferred that within-channel sediment is the most important source in the Esk. Relationships between suspended sediment concentration and flow show that sediment inputs from these sources are generally through low-magnitude, high-frequency processes such as subaerial weathering, and occasionally through episodic high magnitude processes such as bank failure or debris jam removal. Anticlockwise hysteresis, which implies sediment inputs from non-channel sources, occurred at low peak suspended sediment concentrations, when in-channel sediment had been exhausted by a previous event. Non-channel sediment sources are of overall lower importance due to the low level of connectivity in the catchment and the low intensity land use.

The fourth objective was to assess the effect of spatial variability in channel and catchment characteristics on relationships between flow and suspended sediment transport. Catchment mapping showed that channel bank erosion is an important sediment source in the upper main Esk and tributaries excluding Commondale Beck, Baysdale Beck and the Murk Esk. In-channel sediment storage is significant in the upper main Esk and all tributaries except Baysdale Beck and the Murk Esk. These two primary inputs, being from within the channel, both contribute to the clockwise hysteresis which dominates the within-storm sediment behaviour. Above Danby local within channel sediment sources have a relatively high threshold for mobilisation because they are predominantly sand. Their transport results in simple clockwise hysteresis during high magnitude events. Dominant sediment sources above Grosmont are found in the tributaries, rather than the main channel, although sediment is still predominantly from in-channel sources. It is thought that land drains may be extensive in the valleys of Glaisdale and Great Fryup Dale and, together with steep valley slopes around Glaisdale, increase catchment sediment inputs to these tributaries. These factors may help explain the more complex hysteresis patterns seen at Grosmont.

The implications of the study for management are that reduction of sediment supply from within-channel sources, primarily channel bank erosion and poaching, should be a priority. Specifically:

1. Stabilisation and vegetation of slumping channel banks on the main Esk above Lealholm.
2. Stabilisation of eroding banks in tributaries, with Great Fryup Beck and Danby Beck as priorities.
3. Prevention of livestock poaching, with the main Esk below Six Arch Bridge and Great Fryup Beck as priorities, but also in upper Glaisdale Beck, Danby Beck and Tower Beck.

This study has shown the value of using a range of methods to quantify suspended sediment fluxes and of using knowledge of the catchment and channel morphology to provide a process-based explanation for trends. From a geomorphological perspective this allows a better understanding of how catchment and fluvial processes operate, while from a management perspective it helps to identify the most effective way to manage fine sediment in the catchment.

7.2. Limitations and further work

The obvious limitation to this study is that monitoring was restricted to a six-month period. Difficulties with some pieces of monitoring equipment further reduced the extent of continuous monitoring. Because of this timescale, the study was designed to look at short-term variations in suspended sediment flux, at the between- and within-storm scale. A longer period of monitoring would further improve understanding of fine sediment dynamics in the Esk in several ways. Firstly, it would show whether the patterns of flow and suspended sediment concentration over the six months are representative of the longer term trends in the catchment. Secondly, monitoring of within-storm suspended sediment dynamics in a larger number of events would show more clearly the factors important in determining hysteresis. Thirdly, if monitoring was carried out for several years, seasonal trends in suspended sediment dynamics may emerge, which would give further information about how suspended sediment supply and transport processes operate.

Mass flux sampling is a useful way to increase the spatial resolution of fine sediment monitoring, although at a coarser temporal resolution. It was able to show spatial patterns in sediment yields over a time period of three to four weeks. Continuing the mass flux sampling over an increased length of time would also show longer-term trends in sediment transport rates and stronger spatial trends may emerge. Mass flux data from a longer period would allow the use of multiple regression analysis between yields and flow variables and may show more clearly whether flow variables have different effects at each of the sites. It would be interesting to continue to monitor Butter Beck, to find out how long it takes for the sediment transport rates in this tributary to return to pre-disturbance levels.

The analysis of mass flux yields shows that they are highly variable, both spatially and temporally. The trends in the data show that at least some of the variability is due to the large-scale sediment mobilisation and transport mechanisms operating in the various tributaries, reaches and sub-catchments. However, other factors must also be taken into account. The positioning of the sampler in the channel is likely to have an impact on the sediment yield collected. Variation between the two sets of samples from Danby shows that time-integrated sediment transport is not spatially uniform, even within a small reach of the channel. The influence of local sediment supply and transport processes and the distribution of suspended sediment within the river cross section may account for some of the variability in mass flux yields at other sampling sites, particularly where local sediment sources are particularly mobile. Blockage of the samplers by debris was observed on several occasions and may also account for some of the variability in yields. The analysis of mass flux yields in relation to discharge assumes that all channels have similar discharge fluctuations to those at Danby. If this is not the case then any significant variations in discharge between channels may also be the cause of differences in the relative sediment yields calculated. Records of stage at each of the sampling sites would be needed to test this further.

Calculations of relative loads and specific sediment yields from the mass flux samplers used a weighting based on the channel bankfull cross sectional area. The accuracy of this method is limited because of measurement uncertainties and because the frequency of bankfull discharges is unlikely to be constant between sites. The limitations are discussed in more detail in Section 4.2.1. A distributed flow model for the Esk catchment would allow more accurate estimates of the relative discharges at each of the sampling sites and hence better estimates of rates of sediment flux in the channels. Despite these limitations, mass flux sampling proved to be an extremely useful indicator of spatial trends in sediment yields. It is an inexpensive and time-efficient method of data collection and therefore has strong potential for wider use. Further work would be useful to quantify the level of precision and accuracy of the samplers by comparing the results from several samplers at the same site and by comparing mass flux estimates to measures of absolute loads at sites where these can be calculated. This would supplement the work of Phillips *et al.* (2000), who tested the trapping efficiency of time-integrated mass flux samplers.

The use of catchment mapping was an important way of providing a physical basis for interpretation of suspended sediment dynamics. Mapping of the catchment and channel characteristics at different times of year would allow greater understanding of how sediment transport processes vary seasonally and would supplement an extended monitoring period.

Although excess fine sediment is known to silt up salmon spawning redds, it is not known to what extent the fine sediment fluxes monitored in this study contribute to silting up of the gravels in the Esk. Some work has been done in other catchments to quantify the rates of siltation of gravels and the factors contributing to this (e.g. Lambert and Walling, 1988; Acornley and Sear, 1999; Walling and Amos, 1999). From a management perspective, an extension to this study would be to investigate the rate of fine sediment infiltration into the channel bed in different parts of the Esk. Relating siltation to suspended sediment transport dynamics would show whether the two are explicitly linked, or whether certain fractions of the fine sediment load contribute more to silting of gravels. It is probable that the finer fractions of sediment are rapidly flushed through the system, while coarser silts and sands are deposited more readily (Acornley and Sear, 1999). In the Esk the spatial differences in dominant grain size may, therefore, have an influence on the spatial extent of the siltation problem in the Esk. Linking the spatial extent of siltation with a survey of the locations of salmon redds and the distributions of any other species with specific fine sediment needs would show more clearly which parts of the Esk are particularly vulnerable to increased fine sediment transport and allow management to focus on these areas.

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